GLOBAL PERSPECTIVES, LOCAL KNOWLEDGE

Proceedings of the Biennial Conference
of the Australian Association of von Humboldt Fellows
in association with the New Zealand Association of von Humboldt Fellows

20–22 November 2015, Hobart, Tasmania

THE ROYAL SOCIETY OF TASMANIA
1843

Papers and Proceedings of

the Royal Society *of* Tasmania

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Edited by M. Davies and T. R. Finlayson
and published by the Society

Volume 150, Part 1
August, 2016

Published by
The Royal Society of Tasmania
GPO Box 1166
Hobart, Tasmania, Australia 7000

www.rst.org.au

31 August 2016

ISSN 0080-4703

Cover photograph: Alexander von Humboldt, by Friedrich Georg Weitsch, 1806. Source: Wikimedia Commons

Print Tasmania

PAPERS AND PROCEEDINGS OF THE ROYAL SOCIETY OF TASMANIA

VOLUME 150(1)

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Tasmania
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UNIVERSITY of TASMANIA

Publication of this volume was generously supported by the Government of Tasmania and the University of Tasmania.

THE ROYAL SOCIETY OF TASMANIA

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PREFACE TO PROCEEDINGS

As those who venture into some of Tasmania's wilderness areas and national parks will know, we have many geographical references to the name "Humboldt". So it is worldwide, with all such features named for Baron Alexander von Humboldt, the early nineteenth century German aristocrat: natural scientist, diplomat, linguist, explorer, adventurer and humanist, one of the last great polymaths, forerunner of Darwin, and founder of ecology.

The modern Alexander von Humboldt Foundation was inaugurated by the German Government in 1953, to follow von Humboldt's own personal philanthropy, as an institution to support foreign scientists of all disciplines, to work collaboratively with hosts in Germany, and to carry that experience back to their own countries to further scientific advancement, education, and cultural exchange. Today more than 25 000 such individuals worldwide have received significant long-term support from Alexander von Humboldt Fellowships and grants; amongst these are several hundred Australians and New Zealanders, whose experiences have forged career-long links with colleagues in Germany and with German culture and society.

The 2015 biennial conference of the Australian and New Zealand Associations of Alexander von Humboldt Fellows was held in Hobart, at the University of Tasmania's prestigious Institute for Marine and Antarctic Studies (IMAS) building — a fitting venue for the geographical reach and scientific passions of von Humboldt. We are delighted that we are able to publish our proceedings collection for this meeting, under the auspices of the *Papers and Proceedings of the Royal Society of Tasmania* — another institution whose mission also clearly resonates with Alexander von Humboldt's. In fact, von Humboldt's reach has indirectly already been felt here for quite some years: the stunning mounted displays of beetles at the Tasmanian Museum and Art Gallery, which locals young and old come to admire, are a donation of the collections of the late Dr George Bornemissza, the former CSIRO entomologist and von Humboldt Fellow, who ran the transformative Australian dung beetles project. George received his Alexander von Humboldt award at the start of his career, and is celebrated as one of our most distinguished alumni.

Our cooperation with The Royal Society of Tasmania also featured in the opening of our conference — a gala evening event at Government House, with a public address, and subsequent reception in elegant surroundings hosted by Her Excellency Professor the Honourable Kate Warner AM, Governor of Tasmania (pl. 1). The talk, by Dr Brandon Menzies from the University of Melbourne, entitled "Thylacine DNA — life after death" also returned to a theme deeply embedded in the Tasmanian psyche. On this occasion, the audience was treated to a scientific coup and world premiere: the first public unveiling and presentation of a draft assembly of the complete thylacine genome. The results that Brandon reported on were the outcome of his work on thylacine and marsupial genetics with German colleagues during his recent tenure as an Alexander von Humboldt Fellow in Berlin, as well as that of his Australian laboratory.

The pattern of colloquia in the von Humboldt biennial series always reflects the broad and interdisciplinary concerns of the von Humboldt family (pls 2, 3). Our topics this year ranged far and wide — from astrophysical and cosmological questions, such as potential variations of the fundamental constants (and presciently, on physicists' longstanding prediction of gravitational waves, that have since been sensationally confirmed); to visually guided decision-making and universal language in foraging honeybees; to that notorious and infamous US chemist Thomas Midgley Jr. — inventor not only of anti-knock lead petrol additives, but also of chlorofluorocarbons for refrigeration!

PLATE 1 — Friday 20 November: Opening event in the ballroom at Government House (jointly with The Royal Society of Tasmania). Dr Brandon Menzies' address "Thylacine DNA: life after death" featured the release of the first draft assembly of the complete thylacine genome. (Photo Simon Ellingsen)

PLATE 2 — Dr Katrin Amian (Alexander von Humboldt Stiftung) addresses the plenary session in the Institute of Marine and Antarctic Studies (IMAS) lecture hall, on behalf of the Foundation, with an update on its funding programmes and new initiatives for research support and German-Australian scientific cooperation. (Photo Simon Ellingsen)

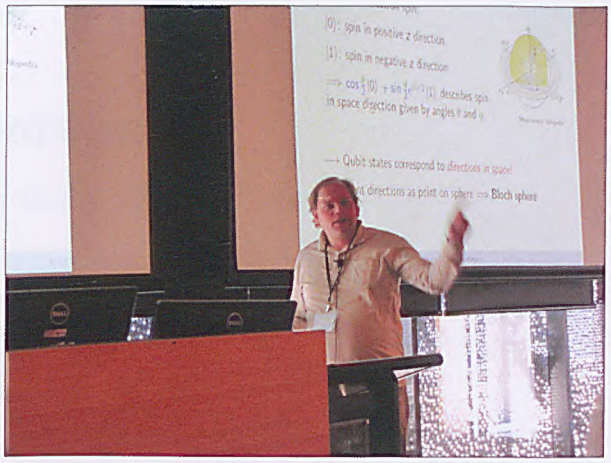

|0⟩: spin in positive z direction
|1⟩: spin in negative z direction
Qubit states correspond to directions in space!
Bloch sphere

PLATE 3 — Dr Christopher Eltschka (Institute for Theoretical Physics, University of Regensburg) explains the intricacies of entanglement and monogamy in quantum information science. (Photo Simon Ellingsen)

Perhaps we have his match in Tasmania, in the person of Robert Sticht, geochemist at Mt Lyell who oversaw the reduction process of sulfide ores that made Queenstown and Tasmania at the turn of the century a world leader in acid rain! Alexander von Humboldt would have appreciated the careful and rigorous work of Gustav Thureau, first Tasmanian Government mining geologist whose career we heard about; he could not have known anything about molecules, still less molecular structure, but he would have been amused to hear that significant puzzles remain in the unravelling of the properties of that most basic and vital of substances, H_2O.

A sample of our presentations is included in our collection here (the complete programme of talks is provided as an appendix to this volume). We also include the inspiring address given to us in the official part of the programme at the conference dinner by Dr Christoph Müller, Ambassador for Germany. The after-dinner presentation on some of the work of Alexander von Humboldt and the ethos of the Foundation was presented by Professor Peter Rathjen, Vice-Chancellor of the University of Tasmania. Both of these contributions added perspective to the significance of our conference, and of the von Humboldt vision itself in the advancement of science and society.

In closing, the invitation from the Governor to host the opening lecture as a joint Royal Society of Tasmania/ Alexander von Humboldt associations event undoubtedly provided a significant drawcard for the conference, which attracted our largest ever attendance of nearly 100 participants, and we are extremely grateful to Government House for this support. It goes without saying that the success of the conference has as usual been guaranteed (*gewährleistet*) through significant financial underpinning provided by the Foundation, through a Humboldt Kolleg grant, as well as the German Embassy, the University of Tasmania, and the Deutscher Akademischer Austauschdienst, all of which we deeply appreciate. We also acknowledge the unflinching administrative and logistical support of Mrs Karen Bradford, School Executive Officer, School of Physical Sciences, as well as that of Mr Sean Dwyer. The local committee is also grateful to our association's executive (President Professor Gabrielle MacMullen, Secretary Associate Professor Trevor Finlayson and Treasurer Professor Gary Bryant) for their constant guidance and encouragement, through their ready responses via email contacts and regular teleconferences, and for the benefit of their good judgement and experience in matters of protocol and planning.

Peter Jarvis
Hobart, April 2016

For the organising committee: Professor Simon Ellingsen, Assoc. Professor Michael Gardiner, Dr Peter Jarvis (chair), Dr Nathan Kilah and Professor Jeff Malpas.

ADDRESS AT THE CONFERENCE DINNER

by Dr Christoph Müller, Ambassador for Germany

It is a great pleasure and indeed an honour to address this distinguished forum and have the opportunity to meet with members of one of Germany's most prestigious science organisations at their Biennial Meeting. Attending the meetings of the Australian and New Zealand Associations of von Humboldt Fellows has been a continuum during the last four years of my posting in Australia: only three weeks after arriving in Australia in 2011, I had the pleasure of attending my first "Humboldtianer" meeting, followed by a Humboldt Colloquium in 2013, and this year we meet again in Hobart – the first time that the meeting is held in Tasmania.

To date, the Humboldt-Foundation has supported 616 Australians and 133 New Zealanders as well as 150 Lynen Fellows. Nearly 1000 academics form an Australian-New Zealand network of Humboldtians. This network lives through the work of the Associations of fellowship holders. Only due to these Associations is it that the Alexander von Humboldt Community in Australia and New Zealand presents itself as a strong and thriving alliance with a great number of current and former fellowship holders working at the forefront of academic cooperation and progress.

Intercultural exchange in science was triggered by Humboldt himself, and it is Humboldtian in character that much of the inspiring research presented at the conference was only possible through international exchange and collaboration. This is reflected in the theme of this meeting: "Global Perspectives, Local Knowledge". We are right at the core of one the most decisive developments in international science: enhancement of international scientific cooperation. This is key to success at a time when the world is becoming an increasingly interconnected global network.

Occasions like this conference provide the perfect setting for researchers to interact and to receive new impulses for future projects. These networking opportunities are of growing significance since the educational and research sector worldwide has undergone major changes. The allocations of responsibilities between public and private research are in a state of flux, opening a broad range of study and research possibilities for students and scientists worldwide.

What is the German Government doing about it these days? Despite Germany's excellent reputation as an educational stronghold, it is becoming increasingly challenging for German universities to compete in the globalised education market. The only way to meet these challenges is to realise that there cannot be excellence in education without international relations at its core. If Germany, as one of the world's most innovative and export-oriented nations, wants to stay at the forefront of research developments, it is of paramount importance to promote cooperation with universities and other educational providers worldwide.

Germany is a country with few natural resources and economic growth depends on science and innovation. Germany therefore invests heavily in Research and Development, including internationalisation of science and research. Despite general cuts to the federal budget in recent years, the German government has increased expenditure for R&D by 65% since 2005 to 14.9 bn Euro in 2015, with the German industry also being a major investor in science. This investment translates into growth: Germany is a world-leader in export of R&D intensive goods and holds a 12% share of world trade in research intensive products. Since 2005 over 100 000 new jobs were created in the German research sector.

Germany also supports a variety of initiatives, programs and foundations to foster international exchange in science and research – the Humboldt Foundation and the German Academic Exchange Service are two well-known and highly successful examples. The German-Australian academic communities have developed close ties, with currently nearly 600 cooperation agreements involving German and Australian universities.

Germany has a strong interest in strategic bilateral relationships with Australia. After signing of the Berlin-Canberra Declaration of a Strategic Partnership in 2013, the high-level Australia-Germany Advisory Group (AGAG) was established in 2014 to discuss how bilateral relations could be intensified, with cooperation in science, education and innovation at the forefront. Only a week ago, on 13 November 2015, the recommendations of the Advisory Group were presented to Chancellor Angela Merkel and Prime Minister Malcolm Turnbull in Berlin.

As we can see, Australia and Germany nurture intensive ties concerning research, with much more potential to explore. But successful developments like this would not have been possible without continuous activities by educational institutions such as the German Academic Exchange Service and the Alexander von Humboldt

Foundation, both of which play an important role in maintaining and expanding scientific cooperation between Germany and Australia.

The German Embassy is pleased to be able to support this Humboldt conference, and to encourage continued and productive German-Australian and German-New Zealand research collaborations.

I wish all the members of the Australian and New Zealand Associations of von Humboldt Fellows a successful and thought-inspiring conference.

Dr Christoph Müller
Ambassador
Embassy of the Federal Republic of Germany, Canberra

MT JOHN OBSERVATORY: THE FIRST 50 YEARS

by J. B. Hearnshaw

(with ten plates)

Hearnshaw, J.B. 2016 (31:viii) Mt John Observatory: the first 50 years. *Papers and Proceedings of the Royal Society of Tasmania* 150(1): 1–8. ISSN 0080-4703. Department of Physics and Astronomy, University of Canterbury, Christchurch, New Zealand. Email: john.hearnshaw@canterbury.ac.nz

Mt John Observatory at Lake Tekapo is New Zealand's only professional research observatory. It was founded in 1965 as a joint institution of the universities of Pennsylvania and Canterbury, though the American participation disappeared after 1980. Some of the successes of the past 50 years and also the numerous problems that arose are described here. Four telescopes have been established at Mt John, including the 1.8-m MOA telescope in 2004, dedicated to microlensing. Astro-tourism has flourished in the past decade.

Key Words: observational astronomy, New Zealand, optical telescopes, stellar spectroscopy, gravitational microlensing, astro-tourism.

INTRODUCTION

The Mt John Observatory at Lake Tekapo in the central South Island of New Zealand was founded in 1965 by the universities of Canterbury and Pennsylvania, after a site survey initiated in 1962. The key players were Prof. F. Bradshaw Wood at Pennsylvania and Frank Bateson, a New Zealand amateur astronomer who conducted the site survey and became the first astronomer-in-charge at Mt John.

The motivation for establishing the observatory was to give Pennsylvania astronomers access to the southern sky, especially for variable and binary star observations. At this time astronomy was just starting as a discipline for teaching and research at Canterbury, but local support for the new observatory to provide the necessary logistics was seen as essential. Pennsylvania offered and sent a large 45-cm aperture refractor telescope dating from the 1890s, known as the Brashear telescope. It was formerly installed at the Flower Observatory near Philadelphia. This was to be the major telescope at Mt John and it arrived in 1963 after refurbishment. Fortunately it was never installed, as it represented outmoded technology and would have required a very large dome and building.

Bateson obtained a large lottery grant of £30 000 (about $1.2 million in today's money) to establish the observatory, and four buildings were erected using these funds (see pl. 1). But the money ran out before the Brashear telescope could be installed. There is some irony in the fact that Mt John depended on the Brashear telescope as the primary telescope to justify its foundation, yet the instrument has now spent some 50 years in storage without making one observation in New Zealand. It will soon be installed near Mt John for public outreach.

SOUTHERN HEMISPHERE OBSERVATORIES IN THE 1960s

In 1960 there were only 10 astronomical observatories south of the equator, compared to 88 in the northern hemisphere (Blanco 1993). Only a few of those in the south were engaged in astrophysics, rather than positional astronomy, and these included Mt Stromlo near Canberra, and the Royal Observatory in Cape Town.

The 1960s and 1970s saw a huge expansion of new observatories, including the Cerro Tololo Interamerican

PLATE 1 — The astrograph building on Mt John under construction in 1964.

PLATE 2 — The US satellite tracking station under construction in 1968.

PLATE 3 — The triple astrograph on Mt John, used for the Canterbury Sky Atlas, 1972.

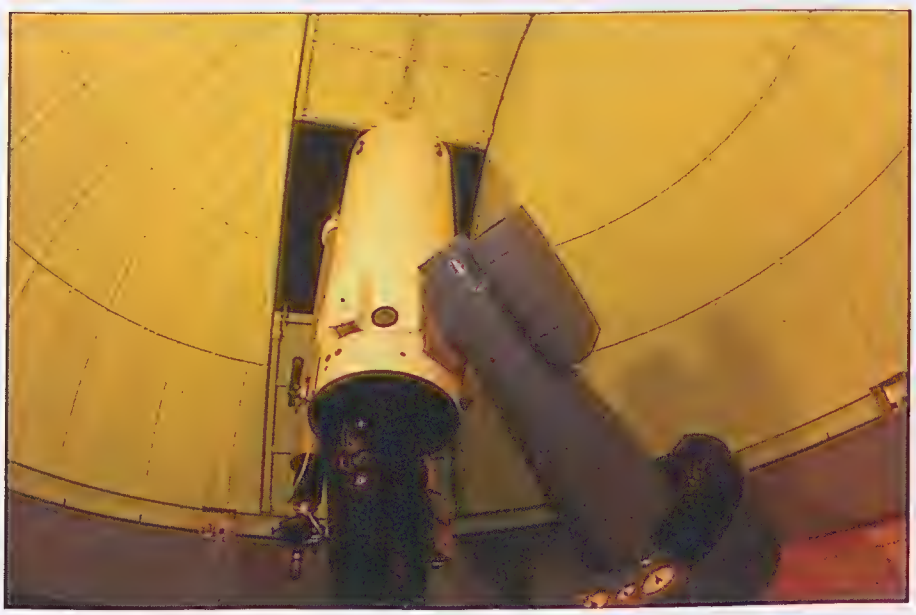


PLATE 4 — The B&C 60-cm telescope with the Cassegrain échelle spectrograph, in 1977.

Observatory (Chile, 1964), the European Southern Observatory (Chile, 1969), las Campanas Observatory (Chile, 1969) and the Anglo-Australian Observatory (New South Wales, 1974). Mt John was part of this thrust to develop new facilities in the south. However, it was supported by just one partner university in the northern hemisphere, so could not compete with the much larger multinational observatories being developed elsewhere, especially in Chile. At this time research in astrophysics was poorly developed in New Zealand universities, and the country was 40 years behind Australia in teaching courses, taking on graduate students and providing observational facilities.

THE US AIR FORCE COMES TO MT JOHN

A significant event in the history of Mt John was the arrival of the US Air Defense Command in 1968, just three years after the establishment of the observatory. A satellite tracking station was constructed near the summit of Mt John, just to the south of the observatory, and on land leased by the University of Canterbury from the Crown. A 476-square metre building (pl. 2) was constructed in 1968, which housed a Baker-Nunn camera, together with offices, accommodation (six bedrooms), a workshop, dining room, kitchen, a communications centre and garages. The whole facility was staffed by American military personnel in uniform, with the approval of the University of Canterbury council, the New Zealand Department of External Affairs (now Ministry of Foreign Affairs and Trade) and the strong support of the University of Pennsylvania, with the claim that "the work was unclassified and the results would be freely available" (Hearnshaw & Gilmore 2015).

The presence of the US Air Force did nevertheless bring some material benefits: a sealed road, a crash barrier on the road and a pumped water supply from the lake, which was shared by the observatory from 1971. Before then Mt John had to rely on collected rainwater as its sole supply. Yet it was an extraordinary relationship which would be unconscionable by the standards of today. It was not surprising therefore that in March 1972 a major demonstration (led by the late Owen Wilkes) of some 300 students and activists took place on Mt John against the military presence on university land. Thanks to advance intelligence, some 60 police officers were present; nevertheless, considerable damage was done, mainly to observatory facilities and to the road. The tracking station itself was largely unscathed (Hearnshaw & Gilmore 2015).

The upshot of the demonstration was that the military personnel were replaced by civilians in 1972, and this enabled satellite tracking to continue until 1983 when the US tracking station was closed. This whole episode had several lasting consequences for the observatory, some positive, some negative. In the public's mind, the distinction between the two separate facilities on Mt John was generally not made, and the university observatory was generally associated with a secret military operation. Also, a small block of land around the satellite tracking station was removed from the university's lease and leased directly from the Crown to the US Government. As a result, when the tracking station eventually closed, the university had to re-acquire that land and take over the vacated building at great expense, paying an exorbitant rental to the New Zealand government for its use. On the positive side, the American facility became the building to house Canterbury's new 1-m McLellan telescope in 1986 and the bedrooms, kitchen and dining room became the centre of the observatory's new accommodation facility from that time (Hearnshaw & Gilmore 2015).

EARLY RESEARCH WORK

The first telescopes at Mt John were two small telescopes owned by Frank Bateson (a 40-cm reflector and a 20-cm refractor), the 45-cm Brashear refractor from Pennsylvania, which arrived in 1963 but was never installed, and three astrographic cameras (apertures 10, 15 and 25 cm) for wide-field photographic survey work (pl. 3). The astrographs were originally at the Cook Observatory of the University of Pennsylvania. They were used in the years 1966–1972 at Mt John to produce the Canterbury Sky Atlas (Doughty *et al.* 1972), a 16th-magnitude atlas of the southern sky to complement the Lick Observatory Atlas (Shane 1958, Lick Observatory Sky Atlas 1965). The atlas was recorded on large-format glass plates using a blue-sensitive photographic emulsion. It was one of the first large projects undertaken at Mt John.

Apart from the work on the Canterbury Sky Survey, the main activity at the observatory was the observation of the light curves of southern eclipsing binary stars using a photoelectric photometer. Such observations were the principal interest of Frank Bradshaw Wood and his colleagues (notably William Protheroe and Bob Koch) at Pennsylvania. At first this work was undertaken using Bateson's own 40-cm reflector: from 1970 a 61-cm telescope was installed by Pennsylvania to continue this work. Bateson had meanwhile resigned as astronomer-in-charge on Mt John in 1969 and removed his own telescopes, after the University of Canterbury declined to purchase them at what was considered to be an exorbitant price.

The University of Pennsylvania sent a number of graduate students to Mt John who used the telescopes to observe and analyse eclipsing binary light curves. Typically two students were sent for deployments in New Zealand for a year. The weather was frequently unfavourable for good quality photometric work, and the poor performance of the two reflecting telescopes was an additional hindrance.

NEW TELESCOPES

It was only in the late 1960s that the University of Canterbury became seriously interested in astronomy and started hiring lecturers to teach undergraduate courses in astronomy and to supervise graduate students. At the same time, the university made a commitment to Mt John, when in 1975 a second 61-cm reflector was purchased from Boller & Chivens (B&C) in the US (pl. 4). It, too, was used for photometry and from 1976 a medium-resolution spectrograph was installed. A year later, Canterbury constructed a high-resolution Cassegrain échelle spectrograph for the B&C telescope, enabling detailed analyses of the spectra of bright stars (Hearnshaw 1977, 1978). This type of work proved to be ideal for Mt John, given the many nights which are not fully photometric.

By 1980 it was clear that a new larger telescope was a high priority for Mt John. Given that the departmental workshops employed technicians skilled in mechanical design and construction, in electronics and computer control and in optics, a new project to design and build a 1-m telescope was initiated. Funding came from the university, the Department of Physics, from the lottery and

PLATE 5 — The McLellan 1-m telescope was designed and built at the University of Canterbury in the early 1980s. It is seen here being tested in a university workshop in late 1985 prior to its installation at Mt John in February 1986.

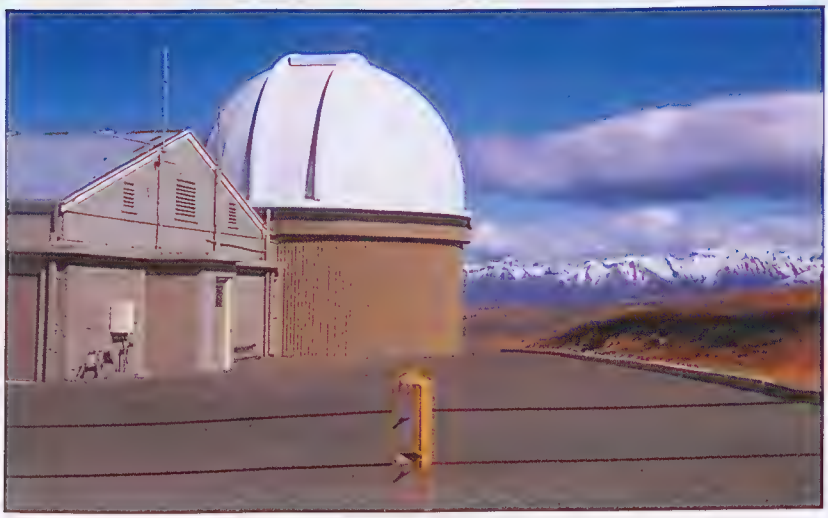


PLATE 6 — The dome of the McLellan 1-m telescope with the Sothern Alps in the background.

PLATE 7 — The vacuum tank of the HERCULES high-resolution spectrograph arrives at Mt John for installation at the 1-m telescope in February 2001.

from a public appeal for funds. Construction commenced in 1981 and the 1-m Zerodur mirror blank was figured in the department by Garry Nankivell from the Department of Scientific and Industrial Research (DSIR) Physics and Engineering Laboratory. The telescope has a Cassegrain Dall-Kirkham optical arrangement with focal ratios of either f/13.5 or f/8, depending on the choice of secondary mirror. The f/8 configuration with field-correcting lenses gave good stellar images over a 1.7° field. The mechanical design and construction were undertaken by university technician, Graeme Kershaw, and the whole project was completed by the end of 1985, with the telescope tested on campus (pl. 5). Installation at Mt John followed in February 1986, in the former US satellite tracking station building after major refurbishment. Part of the overall telescope project was the construction of the 8-m diameter wooden dome (pl. 6) and the construction of a vacuum aluminising plant for the 1-m mirror.

The Mt John 1-m telescope was named the McLellan telescope after the former head of the Department of Physics, Prof. A.G. McLellan. It has been the main work-horse for Mt John for the past 30 years. It has been used primarily for high-resolution stellar spectroscopy, but also for CCD photometry, medium-resolution spectroscopy and astrometry.

THE HERCULES FIBRE-FED VACUUM ÉCHELLE SPECTROGRAPH

A new fibre-fed échelle spectrograph was designed and built in the Department of Physics and Astronomy at Canterbury from 1998–2001. Once again, Graeme Kershaw undertook the mechanical work and Garry Nankivell (then retired and operating from his optical workshop at home) undertook most of the optics. Industrial Research Ltd (formerly DSIR Physics and Engineering Lab) made the large BK7 glass prism for cross-dispersion of the échelle orders. The new instrument was named HERCULES, for the High Efficiency and Resolution Canterbury University Large Echelle Spectrograph. HERCULES was the world's first, fibre-fed, vacuum, échelle spectrograph. The large vacuum tank (4.5 m long, 1.2 m in diameter) enclosed a vacuum at about 3 torr with all the spectrograph components except the 4k × 4k CCD detector being inside the vacuum, and with no moving parts (Hearnshaw *et al.* 2002).

The main components of HERCULES are a 20-cm parabolic collimator, an R2 échelle grating, 20 cm × 40 cm in dimensions, a BK7 cross-dispersion prism weighing 23 kg (probably the largest optical prism made in New Zealand), a folded Schmidt camera comprising a Schmidt corrector plate, a 50-cm spherical camera and a fold flat perforated with a central off-axis hole. A small field-flattening lens immediately in front of the CCD camera also serves as a window between the vacuum and external air.

HERCULES was designed especially for the precise measurement of stellar radial velocities, which are crucial for the detection of extrasolar planets by the Doppler technique. For solar-type stars, radial-velocity precisions of about 3 m/s have been demonstrated from a single spectrum at a resolving power of 70 000. HERCULES was fed by a 25-m-long optical fibre taking light from the f/13.5 Cassegrain focus to a heavily insulated and thermally controlled spectrograph room, which was adapted from the old tracking-station photographic dark room. This room, controlled to about ±0.1°C, provided a very stable environment for the spectrograph operations.

HERCULES went into operation in April 2001 and has been by far the most used instrument on the 1-m telescope since that time (pl. 7). It has been used for studies of binary and variable stars, searches for extrasolar planets, studies of the chemical composition of stars, studies of stellar rotation and of asteroseismology.

THE MOA PROJECT AND 1.8-m MOA TELESCOPE

The MOA project at Mt John was started in 1994 as a collaboration between Auckland, Nagoya and Canterbury universities, with the support of several other institutions in Japan and New Zealand. MOA stands for Microlensing Observations in Astrophysics, and the project aimed to detect extrasolar planets or other dark massive objects in our Galaxy by making photometric observations of the light of stars which were briefly amplified by the gravitational effect of an intermediate lens star or object precisely aligned along the line-of-sight to the source. The amplification effect is detectable when brief alignments of source and lens occur to within about a milli-arc second or better. Microlensing is an effect predicted by Einstein in 1937, though he estimated that such precise alignments would be so rare, they were unlikely ever to be observed (Einstein 1937). The key people in MOA were Professors P. Yock (Auckland) and Y. Muraki (Nagoya), with participation from I. Bond (Massey University at Albany), D. Sullivan (Victoria University Wellington) and J. Hearnshaw (Canterbury).

Following the first detections of microlensing from Australia in 1990, the Mt John MOA project started a few years later, using at first the B&C telescope, modified for a wider field of view. Nagoya University provided a large multi-chip CCD camera. The aim was to search for new microlensing events in crowded star fields in the galactic bulge where about one star in a million can be expected to be undergoing microlensing as a result of the passage of a lens star through the line of sight. The detection of extrasolar planets was a primary goal. A secondary aim in the early years was to search for massive compact lensing objects in the galactic halo, possibly black holes which might account for missing mass in our Galaxy, by observing star fields towards the Magellanic Clouds. The absence of such massive objects in the galactic halo was soon demonstrated by MOA and others. On the other hand, the galactic bulge proved to be a fertile hunting ground for microlensing events, with about 50 or more events being detected in the early years of the project. A decade later, the number of events alerted by the MOA team each year in the galactic bulge had grown to well over 600.

It took MOA about eight years before the first definitive case of an extrasolar planet being discovered from the microlensing light curve (Bond *et al.* 2004). This was for the event MOA-2003-BLG-53, which was jointly discovered with the OGLE (Optical Gravitational Lensing Experiment) team in Chile. The analysis of the light curve indicated the presence of a 1.5 Jupiter-mass gas giant orbiting a low-mass dwarf star (the lens) at a distance of about three astronomical units.

In July 2002, Y. Muraki at Nagoya University obtained a large grant from the Japanese Ministry of Education and Science for the construction of a 1.8-m alt-az wide-field

PLATE 8 — The MOA 1.8-m telescope at Mt John seen at the time of the opening ceremony for the telescope in December 2004.

PLATE 9 — The MOA dome at Mt John with the Two Thumb range seen in the background.

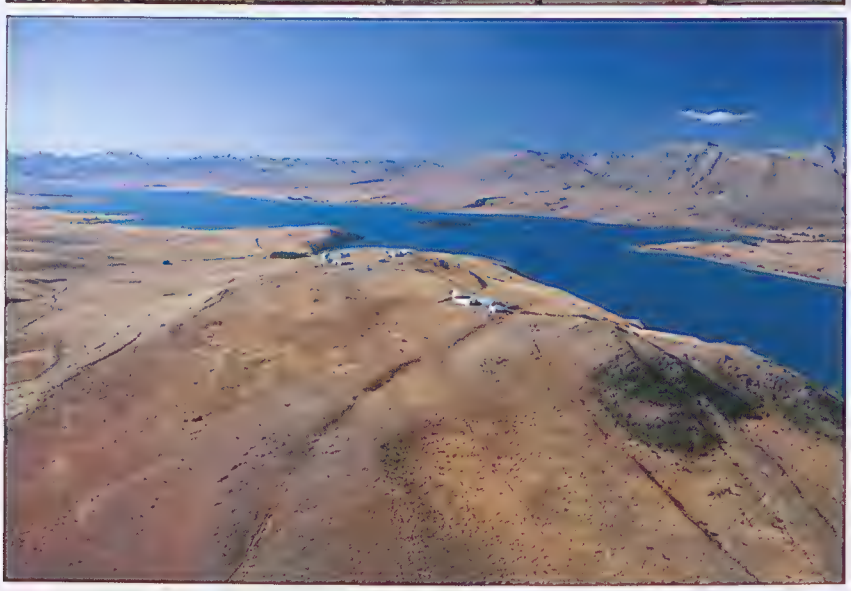


PLATE 10 — Mt John Observatory seen from the air with Lake Tekapo and the Two Thumb range beyond the lake. The McLellan telescope dome is nearest to the camera, the MOA dome is farthest left. The outstanding panorama seen from the observatory and the exceptionally clear air have attracted many thousands of astro-tourists to Mt John in the past 10 years.

imaging telescope to be installed at Mt John for the MOA project. The telescope was constructed by the Nishimura telescope company in Kyoto and installed at Mt John in late 2004 (pl. 8). The optical design was by A. Rakich of KiwiStar optics in Wellington; KiwiStar also made the four prime-focus corrector lenses. The telescope is equipped with a 10-chip CCD camera with 80 million pixels, placed at the telescope's prime focus.

The 1.8-m MOA telescope dedicated to microlensing has led to a large increase in the number of microlensing alerts in the galactic bulge and to the number of extrasolar planets detected by microlensing. Most of the planetary discoveries have been joint efforts with other microlensing groups observing the same event from a range of longitudes, as a full analysis requires constant 24-hour monitoring of an event over several weeks. By late 2014 the MOA project had been operating for two decades, and for almost one decade with the 1.8-m telescope (pl. 9). Twenty-nine extrasolar planets had been discovered by microlensing, with MOA contributing data to all these discoveries. Some of these were only a few Earth-masses, so are presumably rocky objects, in or close to their habitable zones where water can be liquid.

One of the most important results from the MOA project, and perhaps the most significant in Mt John's 50-year history, came in 2011, with the discovery in the Galaxy of free-floating planets, those not attached to any star (Sumi *et al.* 2011). Probably they were ejected from stellar orbits by another massive orbiting planet or by a nearby passing star. The original paper reported ten such objects from observations of short-duration microlensing events, lasting a few hours to about two days, indicating microlensing by gas giant planets. Statistical estimates of the number of free-floating planets in the Galaxy indicate a possible population of several hundred billion, possibly even greater than the number of stars.

MT JOHN AND ASTRO-TOURISM

In 2004 the University of Canterbury gave exclusive tourism rights to the newly-founded company Earth & Sky Ltd at Tekapo, to take visitors to Mt John Observatory. In 2007 Earth & Sky built the Astrocafe on Mt John, comprising a glass atrium around an older and redundant building housing a sky camera. Visitors are able to visit the observatory during the day and go on guided starwatching tours at night. The day visitors come to admire the outstanding view over the Mackenzie Basin and Lake Tekapo (pl. 10), to visit the Astrocafe and some go on guided tours to see the telescopes.

Opening up the observatory to astro-tourists has been almost too successful, with visitor numbers straining the observatory's resources. An estimate of over 120 000 visitors a year is a conservative one based on the count of vehicles driving to the summit of Mt John during the day and on ticket sales for guided night visits. Thousands more walk to the observatory from Tekapo village, but their numbers are not precisely known. In the past decade, Mt John has become a dual-role observatory, catering for both astronomical research and public outreach. Well over a million people have set foot on Mt John in the past decade.

In 2012 an application was made to establish an International Dark Sky Reserve in the Mackenzie Basin and the Aoraki/Mt Cook National Park. The application was made to the International Dark-Sky Association headquartered in Tucson, Arizona, and the outcome was the successful accreditation of the reserve with gold status (the highest awarded). It was the first such reserve in the southern hemisphere, just the third in the world to be inscribed, the largest in the world at 4367 square kilometres and the first to be accorded gold tier status. The reserve built on the lighting ordinances that had been in place since 1981 to protect Mt John from light pollution, as well as the success of Earth & Sky and the scientific reputation of Mt John. The result has been a further large increase in astro-tourism at Lake Tekapo. Mt John is now one of New Zealand's premier tourist attractions, especially for tourists from China and Japan who are coming in ever greater numbers to see a truly pristine unpolluted night sky, which many have never before seen from the large urban centres of their homelands.

CONCLUDING REMARKS AND SUMMARY

Mt John Observatory is now 50 years old. In this time, its reputation for scientific research has grown, based on about 1000 scientific papers in the astronomical literature that have made use of observations at Mt John. By the end of 2014, 82 University of Canterbury graduate students had earned MSc or PhD degrees using Mt John data. In addition, 93 graduate students from other New Zealand universities or from overseas universities (notably, but not only, from the US and Japan) have written theses based on Mt John data. Most of these students have come in person to collect their observations.

Mt John has capitalised on its unique geographical location, as the world's southernmost observatory, and as the only major observatory in its longitude zone. Both latitude and longitude confer distinct advantages for astronomical observing: the latitude because some far southern objects (e.g., the Magellanic Clouds) are circumpolar and visible all year; the longitude because it enables collaborative multi-site observations where time coverage is critical.

Mt John has been able to make a number of key discoveries in its 50-year existence. They include a supernova, a naked-eye nova, three comets, many new asteroids, free-floating planets, one planet in a binary system by the Doppler technique, and two optical transients from gamma-ray bursters. In fact the observatory's main output has been a large number of results on variable stars, binary stars, asteroseismology, minor planet astrometry and gravitational microlensing, too numerous to mention.

In 2015, J. Hearnshaw and A. Gilmore wrote a book entitled *Mt John – the first 50 years: a celebration of half a century of optical astronomy at the University of Canterbury* (Hearnshaw & Gilmore 2015). This richly-illustrated book for the lay reader was published by Canterbury University Press. It gives the full story of the observatory's development and history, including the many personality battles, funding crises and scientific triumphs along the way which characterised the observatory's development.

Today, the battle to continue a viable scientific observatory in New Zealand continues. After the 2011 earthquakes in Christchurch, the University of Canterbury came under extreme financial pressure. Mt John was not directly affected, being 200 km from the quake epicentres, but the financial fallout has squeezed many university facilities. (The scientific staffing levels at Mt John have fallen below a minimum critical mass. The result is a continuing struggle to ensure

that the observatory remains viable as it enters its second half century.)

REFERENCES

Blanco, V. 1993: Brief history of Cerro Tololo Interamerican Observatory, www.ctio.noao.edu/noao/content/ctio-history, accessed 26 April 2016.

Bond, I.A., Udalski, A., Jaroszyński, M., Rattenbury, N.J., Paczyński, B., Soszyński, I., Wyrzykowski, L., Szymański, M.K., Kubiak, M., Szewczyk, O. and 23 co-authors 2004: OGLE 2003-BLG-235/MOA 2003-BLG-53: A Planetary Microlensing Event *Astrophysical Journal Letters* **606**: L155–L158.

Doughty, N.A., Shane, C.D. & Wood, F.B. 1972: *The Mt John University Observatory Photographic Sky Survey and Canterbury Sky Atlas (Australis).* University of Canterbury, Christchurch: 15 pp. plus 46 photographic plates.

Einstein, A. 1937: Lens-Like Action of a Star by the Deviation of Light in the Gravitational Field, *Science* **84**: 506–507.

Hearnshaw, J.B. & Gilmore, A.C. 2015: *Mt John – the first 50 years: a celebration of half a century of optical astronomy at the University of Canterbury.* University of Canterbury Press, Christchurch: 216 pp.

Hearnshaw, J.B. 1977: The Cassegrain Echelle Spectrograph at Mt John Observatory, *Proceedings of the Astronomical Society of Australia* **3**: 102–103.

Hearnshaw, J.B. 1978: An echelle spectrograph, Sky and Telescope **56**: 6–8.

Hearnshaw, J.B., Barnes, S.I., Kershaw, G.M., Frost, N., Graham, G., Ritchie, R. & Nankivell, G.R. 2002: The Hercules Échelle Spectrograph at Mt John, *Experimental Astronomy* **13**: 59–76.

Lick Observatory Sky Atlas 1965: Lick Observatory, University of California, Santa Cruz, CA, USA.

Shane, C.D. 1958: A new sky atlas, *Publications of the Astronomical Society of the Pacific* **70**: 609–610.

Sumi, T., Kamiya, K., Bennett, D.P., Bond, I.A., Abe, F., Botzler, C.S., Fukui, A., Furusawa, K., Hearnshaw, J.B., Itow, Y. and 29 co-authors 2011: Unbound or distant planetary mass population detected by gravitational microlensing, *Nature* **473**: 349–352.

(Accepted 3 May 2016)

RIPPLES IN THE FABRIC OF SPACE-TIME

by Jörg Frauendiener

(with three text-figures and four plates)

Frauendiener, J. 2016 (31:viii): Ripples in the fabric of space-time. *Papers and Proceedings of the Royal Society of Tasmania* 150(1): 9–14. ISSN 0080-4703. Department of Mathematics and Statistics, University of Otago, P.O. Box 56, Dunedin 9054, New Zealand. Email: joergf@maths.otago.ac.nz

Einstein's general theory of relativity is one of the finest achievements of the human mind. It has fundamentally changed the way we think about space and time, and how these in turn interact with matter. Based on this theory Einstein made several predictions, many of which have been verified experimentally. Among the most elusive phenomena that he predicted are gravitational waves, ripples in the fabric of space-time. They are disturbances in the space-time continuum which propagate with the speed of light. This contribution describes some of their properties, their sources and how it is intended to detect them.

Key Words: general relativity, gravitational waves, space-time, black holes, gravitational physics, Einstein's theory of gravitation.

INTRODUCTION

One hundred years ago, on 25 November 1915, Albert Einstein presented to the Prussian Academy of Sciences (Preussische Akademie der Wissenschaften) the final version of the field equations of gravitation which are in accordance with the principles of general relativity (Einstein 1915). He had been working on the problem of incorporating the gravitational force into his theory of relativity, which he published ten years earlier.

The main new ingredient into what he called the general theory of relativity is the formulation of the principle of equivalence. This is the formalisation of the experimental observation going back to Galilei that "all bodies fall at the same rate". Within Newtonian mechanics we can see the implications of this by writing down Newton's second law

$$\mathbf{F} = m_i\,\mathbf{a}$$

for a body with mass, m_i acted upon by a force, **F**. Here, we use the notation m_i to indicate that it is the *inertia* of the mass which resists the attempts of the force to accelerate the body: the larger the *inertial mass*, m_i, the smaller the acceleration, **a**. If the force is the gravitational pull exerted on a small body, *S*, by another body, *B*, such as the Earth, then

$$\mathbf{F} = m_g\,\mathbf{g}.$$

Here, **g** is the gravitational acceleration created by the pulling body, *B*, in case of the Earth the magnitude of this vector is 9.81 m/s^2 at the Earth's surface, and we use m_g to indicate that we use the *gravitational mass*, that property of a body that responds to gravitational pull. Putting the two equations together we find

$$m_i\,\mathbf{a} = m_g\,\mathbf{g}.$$

The experimental fact that all bodies fall at the same rate, i.e., that they all respond in the same way to a gravitational pull, **a** = **g**, can be realised only if the equality $m_i = m_g$ holds. Therefore, there cannot be any difference between the inertial and the gravitational properties of a mass irrespective of its material or its interior constituents. *Inertial* and *gravitational* mass are equivalent. This is the (weak) principle of equivalence. It is the foundation on which the general theory of relativity is built upon. It is therefore essential that it is continuously checked experimentally with as many different and more accurate experiments as possible. In laboratory experiments the equivalence of inertial and gravitational mass could be checked with an accuracy of 10^{-14} (Baeßler *et al.* 1999). In 2016 a satellite experiment called MICROSCOPE (Touboul *et al.* 2012) will test the weak equivalence principle with a projected accuracy of 10^{-17}.

When the principle of equivalence is valid, i.e., when all bodies respond in the same way to the gravitational pull of a massive object, then it makes sense to attribute the cause of the resulting motion of a body to the space and time continuum in which the motion takes place. This implies that space and time acquire geometric properties which *determine* the motion of bodies under the influence of gravity.

However, this also means that the geometry of space and time is influenced by the presence of masses such as our Sun or even larger massive objects such as neutron stars, galaxies or even black holes. More precisely, the presence of a massive object causes the space and time continuum to curve. This means that the space and time continuum can be described in a way very similar to curved surfaces such as a sphere or a torus.

The special theory of relativity had already drastically changed the way we think about space and time. The experimental fact that the speed of light is the same in all reference frames implies that time and space are intimately interwoven with each other and cannot be separated in a way which would be valid for all observers. In the words of Hermann Minkowski (address to the 80th Assembly of German Natural Scientists and Physicians on 21 September 1908):

> *Henceforth, space by itself, and time by itself, are doomed to fade away into mere shadows, and only a kind of union of the two will preserve an independent reality.* (Hilbert 1911)

This union is called the *space-time*. Combining this insight from the special theory of relativity with the equivalence principle we arrive at the notion of a curved space-time which determines the motion of bodies which are subject only to

gravitation and whose curvature in turn is influenced by the presence of matter. This emerging picture is succinctly summarised with the quotation from John A. Wheeler:

> *Space-time tells matter how to move; matter tells space-time how to curve.* (Wheeler & Ford 2000, p. 235).

The interaction between the curvature of the space-time and matter is mathematically described by Einstein's Field Equation

$$G_{ab} = \frac{8\pi G}{c^4} T_{ab}$$

where c is the speed of light and G is Newton's gravitational constant. It equates the Einstein tensor, G_{ab}, measuring certain aspects of the curvature of space-time, with the energy-momentum tensor, T_{ab}, characterising the dynamical energetic properties of the matter.

A solution of the Einstein equations is a space-time with a metric, a mathematical object which tells us how to measure time intervals and distances at any given point in time and space. This is the fundamental quantity which ties observers with their own private notions of time and space to all experiments that happen in space-time. In this sense, the matter contained in a space-time determines what an observer measures.

According to the Einstein equation, the Einstein tensor equals the energy-momentum tensor. But the Einstein tensor is only "half" of the curvature of the space-time. Another half is contained in the Weyl tensor, C_{abcd}, a more complicated object which represents the degrees of freedom of the gravitational field. This is the object that describes the gravitational waves. The gravitational waves represented in the Weyl tensor and the matter in the Universe represented by the Einstein tensor are coupled by a system of partial differential equations which are called the Bianchi identity. It is a remarkable property and an indication of the intrinsic beauty of the theory that this system of equations is identically satisfied for any mathematical manifold with a metric. When interpreted in the context of general relativity this identity becomes the fundamental relationship between the gravitational waves and their material sources. For a more detailed presentation of the basics of the theory of general relativity in a more accessible language see Penrose (2006).

THEORETICAL BACKGROUND

The theory of general relativity (GR) views space and time as a unified entity, the space-time, which interacts with matter in a dynamical way. It changes its curvature depending on the changes in the matter. Clearly, it is a natural question as to whether the dynamics of the space-time curvature could lead to the presence of wave-like phenomena. Indeed, after a mathematical analysis of the field equations Einstein showed that they can have solutions describing small disturbances, *ripples*, of the space-time continuum which can propagate in a wave-like fashion with the speed of light. Consequently, Einstein (1916) predicted the existence of gravitational waves.

The exact description of such ripples in the fabric of space-time is rather involved. The reason for the complications lies at the heart of general relativity and is an immediate consequence of the principle of relativity, another basis of the theory, which states that there are no distinguished observers (or frames of reference). This implies that the separation of a ripple (disturbance) from the undisturbed space-time cannot be done in a way that all observers would agree upon. This problem is nicely illustrated by the image given in plate 1, which shows a view of the surface of the ocean with many "ripples" of varying sizes. Now the problem becomes obvious: where do we make the cut which separates a ripple from the undisturbed wavy ocean surface? We could say that waves with a wave-length smaller than a given size are ripples but this is an arbitrary choice and not consistent since different observers may have different notions of length (see for instance the phenomenon of Lorentz contraction in special relativity). We could also refer to the height of the water surface above the ground but this would introduce a preferred reference frame (the bottom of the ocean) into the theory which is illegal in GR.

The most successful way to obtain an objective description of gravitational waves consists of an analysis of the asymptotic behaviour. In the analogy with the ocean surface this would correspond to going to the boundary of the ocean, the beach, and watching the waves there. The analysis of the asymptotic structure of the wave-like solutions of GR goes back to the work of Bondi *et al.* (1962) and Sachs (1961, 1962) who proved the main result in that area, namely that gravitational waves carry away energy from a system. Newman & Penrose (1962, 1966) and Penrose (1965, 2010) made use of the conformal properties of Einstein's theory to cast the asymptotic analysis into a geometric framework (see also Frauendiener 2004).

The current efforts in the theoretical studies of gravitational waves are largely based on computational simulations. Einstein's equation is reformulated as an initial value problem for a large system of partial differential equations which are then put on to a computer and solved under several different circumstances (Alcubierre 2012, Baumgarte & Shapiro 2003, Choptuik *et al.* 2015). The goal is to determine the characteristic properties of the gravitational radiation that is emitted by different astrophysical systems. This will help to identify the sources of gravitational radiation when it is detected in the future. Ultimately, the gravitational waves will be used to obtain information about the sources and thereby will help us to understand the structure of the Universe and its contents.

The effect of gravitational waves derives from the properties of the space-time; the fact that it determines what we mean by space and time. Suppose we observe two small particles which are placed in front of us. We measure their distance. Since distance measurement is determined by the metric and hence by the curvature of the space-time this means that changes in the curvature are reflected in changes in the distance between the two bodies (and in changes in time measurements as well). Therefore, when a gravitational wave, i.e., a ripple or disturbance in the curvature of the space-time, goes through, we will see a change in the distance of the two bodies. The characteristic feature of gravitational waves is that they change distances in an anisotropic way. That means that the change is different in different directions: first of all, the waves are transversal so that there is no change in the direction of propagation of the waves and, furthermore, when the distance between two bodies increases in one direction then it decreases in the perpendicular direction. This leads to the two characteristic "plus" and "cross" polarisations of gravitational radiation shown in figure 1.

PLATE 1 — A view of the surface of the ocean. How can we distinguish between "background" and "ripples"?

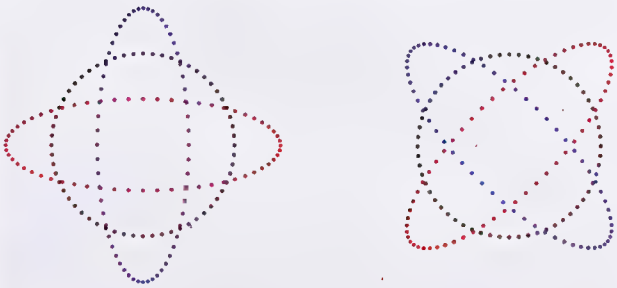


FIG. 1 — The two different polarisation states of a gravitational wave. The pictures show the effect of the "plus" (left) and "cross" (right) waves in a ring of particles (black). Over one wavelength it is distorted first into the red configuration then back to the black one and then into the blue configuration.

SOURCES OF GRAVITATIONAL WAVES

In Maxwell's theory of electrodynamics the main source of electromagnetic radiation is an electric dipole moment which varies (in strength and orientation) over time. Thus, electromagnetic waves are generated whenever charges move; neutral particles do not emit electromagnetic waves.

In contrast, since gravitation affects all masses equally we would expect that any moving mass emits gravitational waves. Indeed, in a complete analogy to Maxwell's theory, one finds that the fundamental source of gravitational radiation in GR is a time-varying quadrupole moment. This result, the famous *quadrupole formula*, was derived already by Einstein (1916). It can be written (in a certain approximation) as follows

$$\left(\frac{P}{Watt}\right) \approx 10^{-52}\left(\frac{\Omega}{Hz}\right)^6 \cdot \left(\frac{L}{m}\right)^4 \cdot \left(\frac{M}{kg}\right)^2$$

From this formula one can estimate the strength of gravitational waves. Let us assume we take a pen which has the shape of a cylinder with a length, L = 10 cm, and a mass, M = 10 grams. Suppose we rotate the pen around its centre of mass with a frequency, Ω = 1 Hz. Then the power, P, of the emitted gravitational radiation is of the order of 10^{-60} Watts. This means that one would need to wiggle some 10^{62} pens if one wanted to supply a 100 Watt light bulb. Therefore, in order to get an appreciable amount of gravitational wave power one needs to look at much larger systems.

The quadrupole formula tells us that the power is most sensitive to the frequency so that it is larger the more rapid the change in the quadrupole is. Also, the larger and more massive the system, the more power output there is. A large system with a changing quadrupole moment is the Earth/Sun system. But even for that system we have a power of only 200 Watts, two light bulbs. If we consider Jupiter instead of Earth we achieve about 5300 Watts. Thus, even for systems of astronomical size one gets a comparatively small amount of power. We need to find large systems which change very rapidly. Such systems do exist. They consist of neutron stars or black holes, very compact, very massive objects which circle around each other very much like the Earth/Sun system. These binary systems are the prime sources for strong gravitational radiation. One particular such system, the so-called double pulsar, was discovered in 2003 (Kramer *et al.* 2006). It consists of two neutron stars each with roughly the mass of the Sun which circle around each other in 144 minutes at a distance of only 850 000 km. The power emitted by this system is of the order of 1045 Watts.

While the binary systems are probably the most prominent sources for gravitational waves, there also exist others. They can be divided into four different kinds according to the signals they emit: inspiral, burst, continuous and stochastic. The first class corresponds to the late stages of a binary system which has already lost so much energy that the two partners are very close to each other and the frequency of the signal is very high. Then the partners will ultimately fall onto each other and merge. The signal is expected to be "chirp"-like.

The burst signal might come from such objects as exploding supernovae or gamma ray bursts. Due to the lack in the microphysical understanding of these systems not much can be said about the detailed structure of the signals.

The continuous signals are expected to come from almost stationary systems such as a young binary or a neutron star with an irregular non-axisymmetric shape (a mountain). These signals are expected to be quite weak and not detectable with the current generation of detectors.

The stochastic signals are the relic of the "big bang" in much the same way as the cosmic microwave background (CMB). The difference is that the electromagnetic waves of the CMB were created at the surface of last scattering (or recombination) at about 300 000 years after the "big bang", while the gravitational waves we would see were created very shortly after the "big bang". The signal will be stochastic and isotropic (i.e., noise from all directions).

OBSERVATIONS

As described in the previous section, gravitational waves are everywhere since every moving mass emits them. However, they are generally very weak. So how do we know that they exist? We have two pieces of evidence for their existence but a direct detection has remained elusive to this day.

The first piece of evidence for the existence of gravitational waves is purely theoretical and consists of the mathematical fact that Einstein's theory which has been tested and confirmed in several other contexts predicts the wave-like

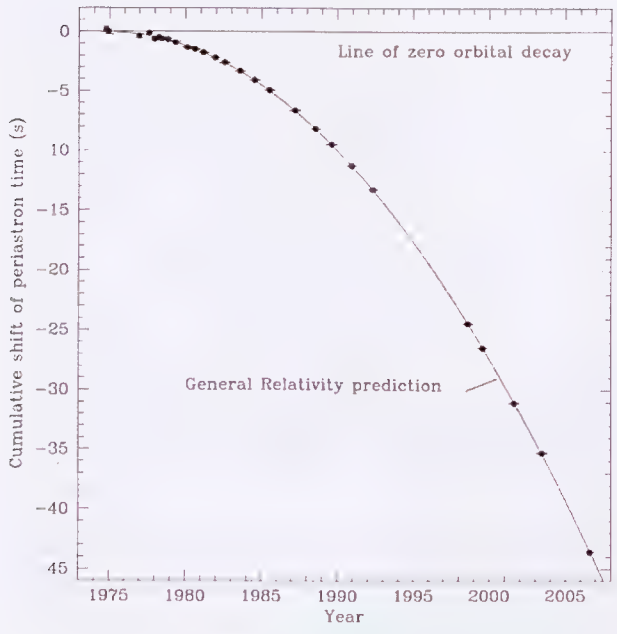


FIG. 2 — The change in the period of the binary pulsar observed and predicted by GR.

PLATE 2 — J. Weber with one of his bar detectors.

solutions which carry energy. Hence, it is very likely that this aspect of the theory is correct as well.

The other piece of evidence is an indirect experimental verification. The first binary system, consisting of a pulsar and an ordinary star, was discovered in 1973 by Hulse & Taylor (1974). It was subsequently monitored continuously and its parameters were registered over a time of more than three decades. It was found that the period of the system decreases over time. This means that the system loses energy, the two bodies come closer to each other so that they rotate faster (just like an ice skater who brings in her arms to perform a pirouette). But the energy that is lost must go somewhere and the most reasonable explanation is that the system emits gravitational waves which carry the energy away. One can estimate the amount of emitted gravitational radiation using the quadrupole formula and, based on that, one can determine the change of the period of the system from the beginning of the observation. The result is the graph presented in figure 2.

The graph shows measurements of the period of the binary pulsar between 1973 and 2007. The horizontal line at the top corresponds to the behaviour when no energy is lost. The solid line gives the behaviour if the energy loss is caused by gravitational waves according to GR and the dots are the actual measurements with their error bars. The agreement is obvious.

In the meantime, several binary systems have been found and observed with the same results. While it is quite comforting to know that these systems behave exactly as Einstein's theory predicts, there remains some uneasiness since we still do not have a direct proof of the existence of gravitational waves.

A direct detection of the gravitational waves is difficult. Not only are their possible sources very far away, the waves by themselves are very weak as we have seen. This means that the detectors must be of a very high quality in order to be able to "see" something. The detection uses the effect of gravitational waves on bodies as discussed previously: either one monitors the distance between free bodies or the force between fixed bodies that is needed in order to keep them in place when the gravitational wave grabs them.

Correspondingly, gravitational wave detectors come in two flavours, laser-interferometers and bar detectors. Historically, the bar detectors were first. The first attempt of detection was made with a bar detector by Joseph Weber (pl. 2) in the 1960s. He used two aluminium cylinders, each about 1.5 m long and 0.5 m thick. When a gravitational wave comes through them it rattles the atoms in the aluminium and causes them to vibrate at a characteristic frequency that is detected using piezo-electric transducers. In 1968, he claimed that he had detected gravitational waves but this was soon disputed and even today we have not seen these waves. Bar detectors are still in use, see for instance MiniGRAIL (De Waard *et al.* 2003) in Leiden (pl. 3).

The disadvantage of bar detectors is that they are sensible only for a very small frequency window dictated by the geometry of the bar. Therefore, most gravitational wave detectors today are based on the laser-interferometric design. The detectors operate like a Michelson interferometer monitoring the length of two arms perpendicular to each other using laser beams which are reflected at the end of the arms by a highly reflecting mirror and brought to interference back at the intersection of the two arms (see fig. 3).

When a gravitational wave goes through it changes the arm-lengths in opposite ways as described in the section on sources of gravitational waves and the relative change is detected. The size of this change is estimated to be at the order of 10^{-22}, corresponding to the inverse ratio of the distance between Sun and Saturn to the diameter of a hydrogen atom. This is a minute change in length which implies that the equipment must be of the utmost quality.

There are currently four interferometers in operation under the umbrella of the LIGO Scientific Cooperation (LSC): the two LIGO detectors in Livingstone, Louisiana, and Hancock, Washington, with an arm-length of 4 km (see pl. 4); GEO600 in Hannover, Germany, with 600 m arm-length and VIRGO in Pisa, Italy, with an arm-length of 3 km. These detectors are operating simultaneously in order to catch coincidences. They have recently been upgraded to a more advanced technology and will soon

start to take data at a much higher sensitivity. Two further detectors are planned: KAGRA in Japan and the Einstein telescope in Europe.

The ground-based detectors in use today are limited in their sensitivity at low frequencies by several sources of noise, the most important one being the seismic noise that is generated by irregularities in the environment. This is the reason why several years ago plans were developed to send a satellite-based detector in an orbit around the Sun. The idea is to have three satellites in a fixed configuration at a mutual distance of several million kilometres trailing behind the Earth and send laser beams between them in order to monitor their relative distances.

This project, called LISA (Laser-Interferometric Space Antenna), went through several ups and downs and its development has been delayed for a number of years. However, on 3 December 2015 the European Space Agency launched a precursor, the LISA Pathfinder mission, to test that two masses can fly through space and maintain their relative positions to the precision required for the operation of a gravitational wave observatory.

THE FUTURE

With the technological advances that have gone into the recent upgrade of the currently operating gravitational wave detectors the community seems to be cautiously optimistic that a direct detection of the gravitational waves will happen within the next five years. Of course, this would be a triumph for the theory of general relativity in that all of Einstein's original predictions have been verified.

However, this is not the only consequence. With the detection of gravitational waves we will have another medium at our disposal in addition to the full spectrum of electromagnetic waves. This will allow us to gain much more information about the Universe and the matter it contains than we currently have. Until now we obtain all our information about the Universe via electromagnetic radiation (light, X-rays, gamma rays, etc.). However, as is well known, these waves are easily reflected, scattered, absorbed and reemitted. Therefore, the signals we receive contain information about all the intervening processes. There is a limit beyond which we cannot see back into the past because the electromagnetic radiation was completely scattered by the hot plasma that first formed after the "big bang". When the Universe had cooled down enough so that the first atoms could form ("recombine") from the plasma, then the photons could travel freely without being scattered. Therefore, electromagnetic radiation cannot provide us with information about the time before the recombination. However, the Universe is completely transparent to gravitational waves which will allow us to get information about times as far back as the "big bang".

Furthermore, the detailed physics of how the radiation is emitted is encoded in both channels of gravitational and electromagnetic radiation. Their combined observation will provide us with many new insights into the microphysics of the sources, such as neutron stars, supernovae and gamma ray bursts.

In summary, the successful detection of gravitational waves will open a new window to the Universe and initiate the new era of gravitational wave astronomy.

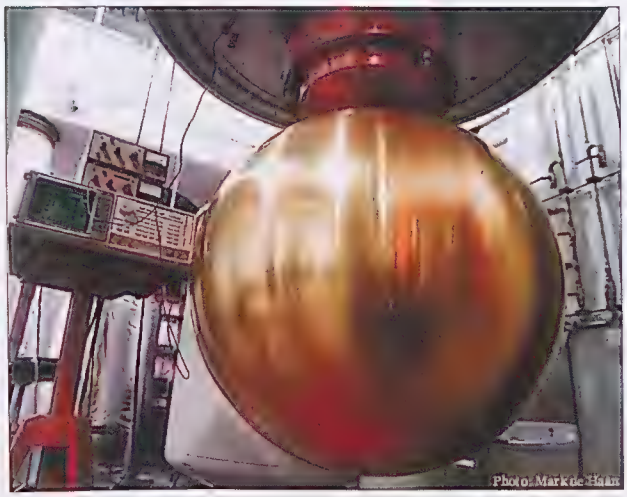


PLATE 3 — The spherical detector MiniGRAIL in Leiden.

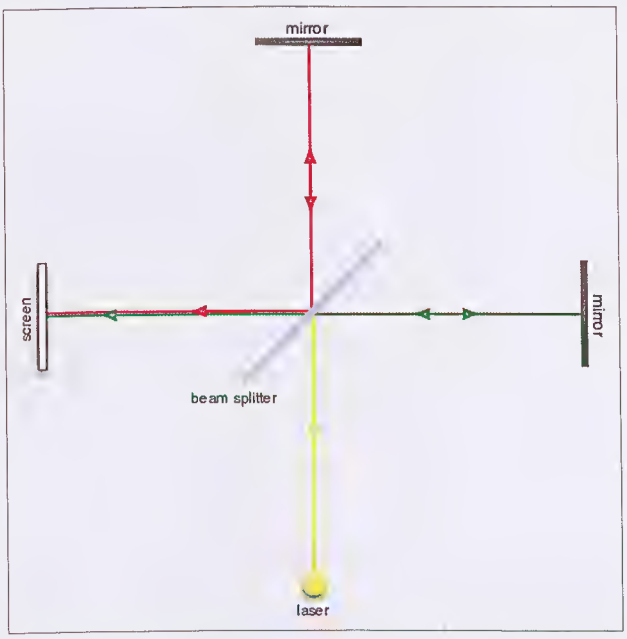


FIG. 3 — Schematic diagram of an interferometric gravitational wave detector. A laser sends light into the interferometer which is split by a splitter into two rays perpendicular to each other. After reflections at the mirrors the beams are recombined and compared.

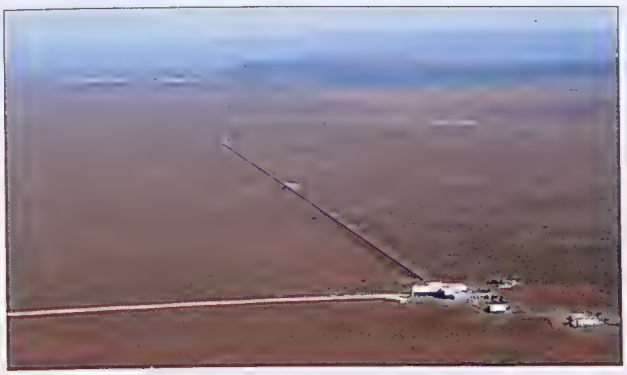


PLATE 4 — An aerial view of the LIGO site in Hancock, Washington. Note the two arms, each with a length of 4 km. The beam splitter and the detection electronics are located in the central building.

NOTE ADDED AT REVIEW STAGE

The future has arrived! While this article was in the reviewing process, the Ligo Scientific Collaboration (LSC) published the details of two detection events: GW150914 (Abbott *et al.* 2016a) and GW151226 (Abbott *et al.* 2016b) were both received by the two LIGO detectors in the USA and were both caused by black holes merging into a single one.

The earlier signal from 14 September 2015 was emitted by two black holes with masses of around 36 and 29 solar masses. They came together within 0.2 seconds having circled around each other with a frequency of up to 250 Hz. They settled into a single black hole with a mass of 62 suns, having emitted gravitational waves with a total energy of the equivalent of three solar masses. To put this into perspective: the most energetic man-made event was the so-called "Tsar Bomba", a soviet hydrogen bomb with 50 mega-tons TNT, which detonated in 1961. This energy output corresponds to a rest-mass equivalent of just 2 kg.

The second event was much smaller. It was recorded on Boxing Day 2015. Again, two black holes collided and merged within 1 second. Their masses were 14.2 and 7.5 solar masses, respectively.

These detections confirmed Einstein's theory twice: they showed that gravitational waves are real, thereby putting an end to a one hundred-year-old uncertainty. But they also confirmed that black holes exist because there are no other currently known massive systems that could have created the first event GW150914. This shows that the Kerr-Newman family of solutions to the Einstein equations is of important physical relevance.

Based on the two detections to date it is estimated that there will be on the order of 1000 detections per year once the detectors have reached their final sensitivity. These are certainly exciting times to be a researcher in gravitational wave physics.

ACKNOWLEDGEMENTS

The author is very grateful to the organisers of the Biennial meeting of Australian and New Zealand Alexander von Humboldt Fellows in Hobart where this paper was accepted for oral presentation.

REFERENCES

Abbott, B.P., together with 1011 other authors, 2016a: Observation of gravitational waves from a binary black hole merger. *Physical Review Letters* **116**: 061102.

Abbott, B.P., together with 969 other authors, 2016b: GW151226: Observation of gravitational waves from a 22-solar-mass binary black hole coalescence. *Physical Review Letters* **116**: 241103.

Alcubierre, M. 2012: *Introduction to 3+1 Numerical Relativity.* Oxford University Press, Oxford: 444 pp.

Baeßler, S., Heckel, B., Adelberger, E., Gundlach, C., Schmidt, U. & Swanson, H. 1999: Improved test of the Equivalence Principle for Gravitational Self-Energy. *Physical Review Letters* **83**: 3585–3588.

Baumgarte, T.W. & Shapiro, S.L. 2003: Numerical relativity and compact binaries. *Physics Reports* **376**: 41–131.

Bondi, H., Van Der Burg, M.G.J. & Metzner, A.W.K. 1962: Gravitational waves in general relativity. VII. Waves from axi-symmetric isolated systems. *Proceedings of the Royal Society London A* **269**: 21–52.

Choptuik, M.W., Lehner, L. & Pretorius, F. 2015: Probing strong field gravity through numerical simulations, *In* A. Ashtekar, B. Berger, J. Isenberg & M.A.H. MacCallum (eds.): *General Relativity and Gravitation: A Centennial Perspective.* Cambridge University Press, Cambridge, 2015: 361–411.

De Waard, A., Gottardi, L., van Houwelingen, J., Shumack, A. & Frossati, G. 2003: MiniGRAIL, the first spherical detector. *Classical and Quantum Gravity* **20**: S143–51.

Einstein, A. 1915: Die Feldgleichungen der Gravitation. *Sitzungsberichte der Preussischen Akademie der Wissenschaften zu Berlin* **2**: 844–847.

Einstein, A. 1916: Näherungsweise Integration der Feldgleichungen der Gravitation. *Sitzungsberichte der Königlich Preussischen Akademie der Wissenschaften* **1**: 688-691.

Frauendiener, J. 2004: Conformal infinity *Living Reviews in Relativity* **7** 2004–1, doi: 10.12942/lrr-2004-1.

Hilbert, D. (ed.) 1911: *Gesammelte Abhandlungen von Hermann Minkowski*, Teubner, Leipzig and Berlin: 871 pp.

Hulse, R.A. & Taylor, J.H. 1974: A high-sensitivity pulsar survey. *Astrophysical Journal* **191**: L59.

Kramer, M., Stairs, I.H., Manchester, R.N., McLaughlin, M.A. Lyne, A.G., Ferdman, R.D., Burgay, M., Lorimer, D.R., Possenti, A., D'Amico, N., Sarkissian, .J, Joshi, B.C., Freire, P.C.C. & Camilo, F. 2006: Strong field tests of gravity with the double pulsar. *Annalen der Physik* **15**: 34–42.

Newman, E.T. & Penrose, R. 1962: An approach to gravitational radiation by a method of spin coefficients. *Journal of Mathematical Physics* **3**: 566–578.

Newman, E.T. & Penrose, R. 1966: Note on the Bondi-Metzner-Sachs group. *Journal of Mathematical Physics* **7**: 863–70.

Penrose, R. 1965: Zero rest-mass fields including gravitation: asymptotic behaviour. *Proceedings of the Royal Society London A* **284**: 159–203.

Penrose, R. 2006: *The Road to Reality.* Random House, London: 1136 pp.

Penrose, R. 2010: Republication of: Conformal treatment of infinity. *General Relativity and Gravitation* **43**: 901–922.

Sachs, R.K. 1961: Gravitational waves in general relativity. VI. The outgoing radiation condition. *Proceedings of the Royal Society London A* **264**: 309–38.

Sachs, R.K. 1962: Gravitational waves in general relativity. VIII. Waves in asymptotically flat space-time. *Proceedings of the Royal Society London A* **270**: 103–26.

Touboul, P., Metris, G., Lebat, V. & Robert, A. 2012: The MICROSCOPE experiment, ready for the in-orbit test of the equivalence principle. *Classical and Quantum Gravity* **29**: 184010.

Wheeler, J.A. & Ford, K. 1998: *Geons, Black Holes, And Quantum Foam: A Life in Physics.* WW Norton & Company, New York: 416 pp.

(Accepted 5 July 2016)

Fe-Ti-V-(P) RESOURCES IN THE UPPER ZONE OF THE BUSHVELD COMPLEX, SOUTH AFRICA

by L.A. Fischer and Q. Yuan

(with four text-figures and two plates)

Fischer, L.A. & Yuan, Q. 2016 (31:viii): Fe-Ti-V-(P) resources in the Upper Zone of the Bushveld Complex, South Africa. *Papers and Proceedings of the Royal Society of Tasmania* 150(1): 15–22. ISSN 0080-4703. Institut für Mineralogie, Leibniz Universität Hannover, 30167 Hannover, Germany, and School of Physical Sciences, University of Tasmania, Hobart, Tasmania 7001, Australia (LAF*); Faculty of Earth Resources, China University of Geosciences, Wuhan 430074, China, and Department of Geology, University of Liege, 4000 Sart Tilman, Belgium (QY). *Author for correspondence. Email: l.fischer@mineralogie.uni-hannover.de

The Bushveld Complex in South Africa is the largest layered intrusion on Earth. Its upper part is known for huge resources of iron, titanium, vanadium and phosphorus. Associated with the layered character of the rocks, these resources are enriched at certain levels of the intrusion, which makes it important to understand the formation processes of those layers. In this paper we give an introduction and overview of recent debates and challenges.

Key Words: layered intrusion, Bushveld, resources.

INTRODUCTION

Iron (Fe), titanium (Ti) and vanadium (V) are important resources for the world's economy. While iron is a major material in many industries, titanium and vanadium have become more important during the past decades. Both, titanium and vanadium are important alloying elements in the steel industry, improving the strength and toughness of steel. These steel alloys are in great demand, especially in the aerospace industry.

Continuous industrial development is reflected in the mine production of these elements and their ores or source minerals, which has greatly increased in the past 20 years. The mining of these resources has more than doubled, except for phosphorus (P) production which has increased to a lesser extent (U.S. Geological Survey 2015) (fig. 1). World demand and limited known reserves of those resources emphasise the importance of gaining a better understanding of the processes of formation of their deposits.

Fe, Ti, V and P never or only rarely occur as native elements in nature. Minerals, rich in one or more of these elements are mined and their components are extracted. One of the most commonly mined minerals for iron is magnetite (Fe_3O_4), which can also contain significant concentrations of titanium. The main source for titanium is ilmenite ($FeTiO_3$). Both Fe-Ti-oxides can contain economically valuable amounts of vanadium. Phosphorus is extracted from phosphate minerals such as apatite ($Ca_5(PO_4)_3(F,Cl,OH)$).

Deposits mined for magnetite, ilmenite and/or apatite can have different origins. Magnetite can be formed by sedimentary, magmatic or biogenic processes. Concentrated magnetite-rich sediment layers are produced by bacteria in marine environments (Devouard *et al.* 1998), volcanic activity (Nystrom & Henriquez 1994) or fluvial transport (Fletcher & Walcott 1991). Ilmenite has a magmatic origin and can be concentrated by fluvial transport (Garzanti *et al.* 2010). Apatite is commonly formed by magmatic processes (Green & Watson 1982) or by biomineralisation

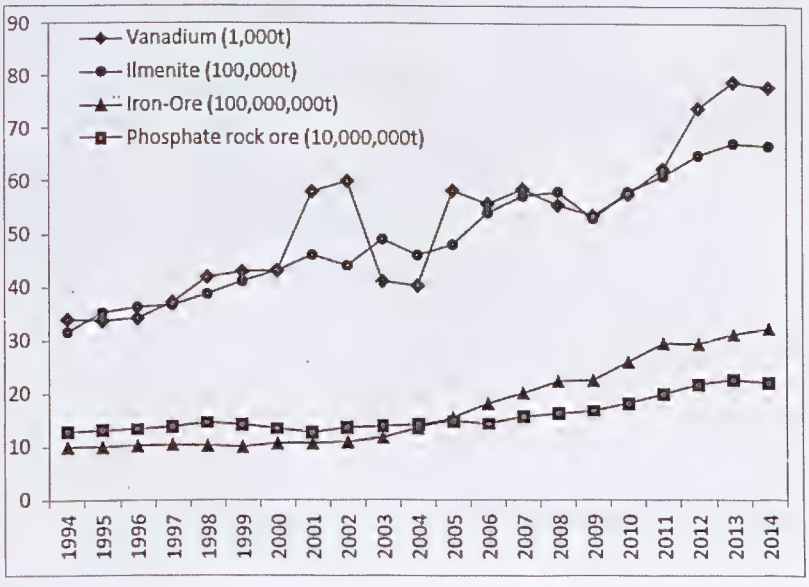


FIG. 1 — Annual world production of vanadium and major resource suppliers for iron, titanium and phosphorus. Units are given in the figure. Ilmenite supplies 90% of consumed titanium (U.S. Geological Survey 2015). Iron-ore and phosphate rocks are mined for iron and phosphorus, respectively. Annual production data are taken from U.S. Geological Survey (2015).

(Hirschler *et al.* 1990). Importantly, all three minerals are also found in high proportions in certain layers in some solidified magma chambers, called layered intrusions (Eales & Cawthorn 1996, Song *et al.* 2013).

LAYERED INTRUSIONS

Layered intrusions are solidified magma chambers, showing a layering of rocks with different bulk compositions. The differences can be expressed in terms of the variety of minerals present and/or their proportions, and also their textures. The layering is a product of processes occurring during cooling of the magma chamber. Magma is derived from a source within the Earth's mantle to the crust, and causes partial melting of the crust due to the heat excess, as well as updoming and rifting due to buoyancy of the ascending magma. Finally, this process results in an intrusion of magma into the crust. The intruding magma can reach the surface, resulting in a volcanic eruption or can remain in the crust, forming a magma chamber. The level to which the magma ascends depends on buoyancy and viscosity, which is controlled by the magma composition and temperature, as well as crustal structures which provide conduits. The magma composition is determined by the compositions of the initial magma ascending from the mantle, crustal partial melts and potentially due to assimilation of magma chamber wall rocks.

The emplaced magmas have temperatures up to 1250°C and are substantially hotter than the crustal host rocks (fig. 2.1). Consequently, the magma cools during and after its intrusion into the crust. Once the temperature is below the liquidus, crystallisation begins. Most crystals sink to the bottom of the magma chamber due to their high density compared to their parental liquid, and form a layer of accumulated minerals (cumulus minerals). With time and progressive cooling more minerals crystallise and settle within the magma chamber, forming horizontal layering until the magma chamber is completely solidified. Since the extraction of crystals from the liquid is accompanied by a change in the liquid's composition, the composition of minerals and thus the rock shows a compositional progression, expressed by the typical layered structure (fig. 2). Rocks formed by crystallisation and settling of minerals are named cumulates.

In nature this process is much more complex. Besides temperature, changes in oxygen fugacity can have dramatic effects on the crystallising phases and thus the path of magmatic evolution (Namur *et al.* 2015). Also changes in the volatile content (H_2O and CO_2) and potential degassing events influence the crystallisation sequence. Moreover, instead of a single crystal composition different minerals can crystallise at the same time, building up a cumulate rock layer. Crystal compositions can change between layers, but also the relative proportions of minerals or their textures can differ. Repeated layers with similar composition are observed in nature. In some cases new magma is injected into an existing magma chamber, affecting the magma compositions and thermodynamic properties of the system which results also in a change of compositions and modes of crystallising minerals. Depending on magma and crystal compositions, crystals can be more buoyant than the magma and therefore float (Campbell 1978, Namur *et al.* 2011). However, these crystals are commonly found in cumulate layers in certain locations. To explain these occurrences other processes besides crystallisation and settling have to be considered (Namur *et al.* 2015).

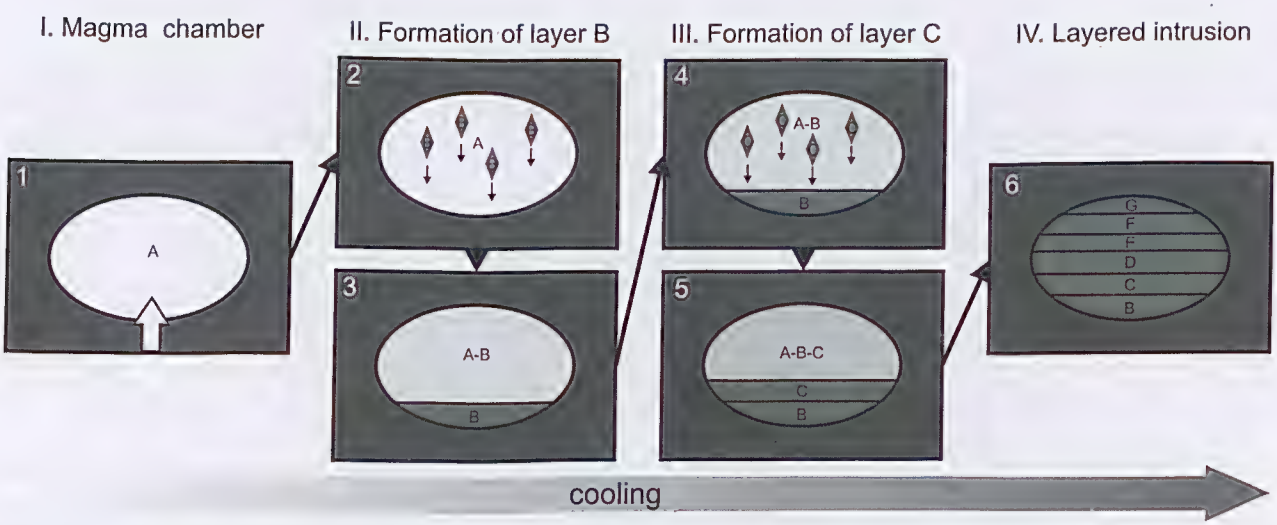


FIG. 2 — Simplified schematic illustration of the crystallisation and settling process in a layered intrusion. The hot magma, with the composition A intrudes and remains in the crust (fig. 2.1). The magma chamber cools down and crystallisation of crystals with composition B starts (fig. 2.2). Crystals settle at the bottom of the magma chamber and form a layer rich in cumulus minerals having the composition B. The residual magma has the composition A minus B (fig. 2.3). Under different conditions (decreased temperature, different magma composition) crystallising minerals have a different composition C (fig. 2.4) and the resulting layer is different from the previous one (fig. 2.5). With continuous cooling crystallisation and settling produce more layers with different compositions until the magma chamber is solidified (fig. 2.6). Note that the composition of the residual magma is also strongly dependent on the volume crystallising from the magma but not shown in this simplified figure.

THE BUSHVELD COMPLEX

The Bushveld Complex in South Africa (fig. 3) is the largest layered intrusion on Earth. Formed by 1 million km³ of magma (Cawthorn & Walraven 1998), it covers a 65 000 km² area with a thickness of 7–9 km, emplaced in three limbs (western, eastern and northern limb). Within this giant volume, the world's major resources of platinum and other platinum group elements (PGE), iron, titanium, vanadium, tin and chromium are hosted. The Bushveld Complex is the world's largest resource of PGE. Discovered in the late 1860s by Carl Mauch, it is still one of the most important mining areas in the world. Major resources of PGEs are hosted in the Merensky Reef (MR) and Upper Group 2 Reef (UG2). Both in general 1.5 m-thick layer packages containing chromite ($(Fe, Mg)Cr_2O_4$) dominated layers. Iron and titanium are concentrated in magnetite and ilmenite-rich layers. Prominent examples are the Main Magnetite layer (MM) and the Magnetite layer 21 (M21).

The chemistry of the Bushveld Complex and of its initial magma as well as later injected magmas has been estimated by several authors (e.g., Davies *et al.* 1980, Van Tongeren *et al.* 2010, Barnes *et al.* 2010). Although accurate magma compositions are hotly debated (Cawthorn 2015), the overall mineral assemblage implies a relatively Mg and/or Fe-rich silicate magma, classified as "mafic". Consequently, the rocks formed from these magmas are mostly mafic rocks. Common mafic minerals for the Bushveld Complex are pyroxene ($(Mg,Fe,Ca)_2Si_2O_6$), olivine ($(Mg,Fe)_2SiO_4$), magnetite and ilmenite.

Zircon U/Pb dating has revealed that the initial emplacement of magma in the Bushveld occurred at 2055.91±0.26 Ma, and the whole intrusion cooled to below 650°C (solidified magma chamber) in 1.02±0.63 Ma (Zeh *et al.* 2015). Cawthorn & Walraven (1998) proposed an even shorter crystallisation time of 200 000 years.

The Bushveld cumulate rocks are divided into the Marginal, Lower, Critical, Main, Upper and Roof Zones and their corresponding subdivisions (Wager & Brown 1968, Cawthorn 2013a), based on mineral assemblages (fig. 4). The initial horizontal layering of the Bushveld intrusion was displaced and is now dipping towards the centre of the body (fig. 4). Cawthorn & Webb (2001) proposed that isostatic adjustment, induced by the huge mass of emplaced magma, is responsible for the tilted layers. Here, we focus on the genetically related Upper and Upper Main Zone (UZa, UZb, UZc and MZu) hereinafter referred as UUMZ.

The Upper and Upper Main Zone

The UUMZ is commonly considered as representing the last injection of magma into the Bushveld magma chamber and is known as a world-class deposit of Fe, V, Ti and P. The Pyroxenite Marker (PM) is located at the base of the UUMZ (fig. 4), indicating a major change of magma composition between UUMZ and the underlying part of the MZ. It is thought that an injection of new magma changed the

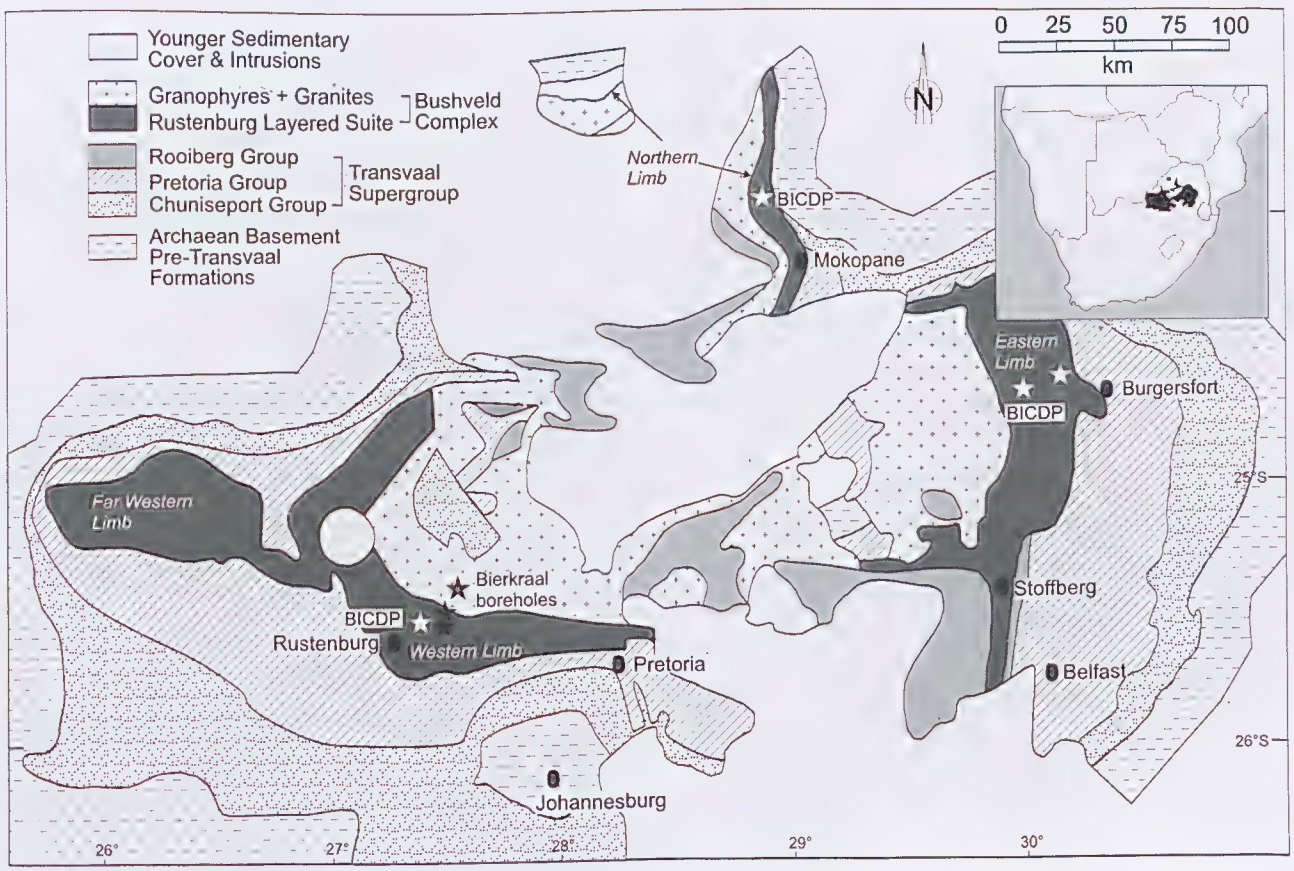


FIG. 3 — Geological map of the Bushveld Complex with location of the Bierkraal boreholes (black stars) and the potential drilling sites of the BICDP (white stars; Trumbull *et al.* 2015). Modified after Barnes & Maier (2002).

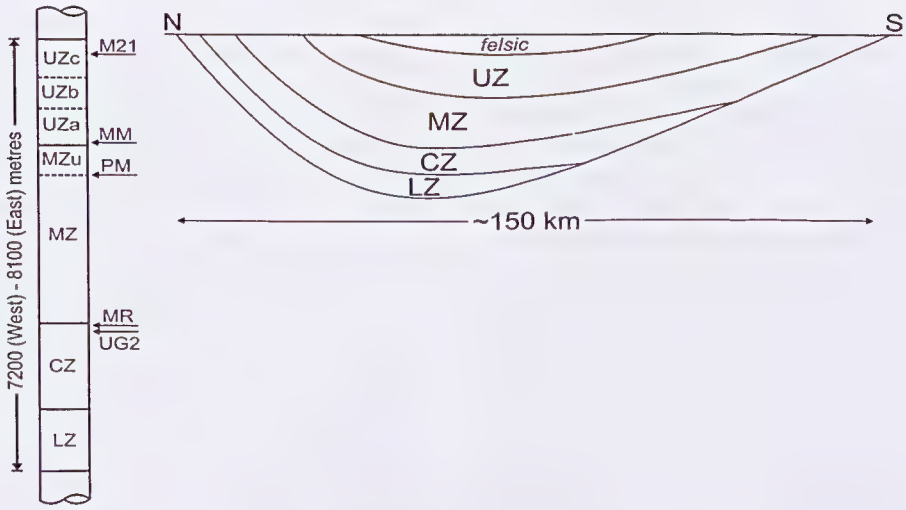


FIG. 4 — Simplified stratigraphic column (left) and cross-section (right) of the western and eastern limb of the Bushveld Complex with Zones and distinctive layers. Lower Zone (LZ), Critical Zone (CZ), Main Zone (MZ) and Upper Zone (UZ) are divided by solid lines. Subdivisions Upper Middle Zone (MZu), Upper Zone a (UZa), Upper Zone b (UZb) and Upper Zone c (UZc) are divided by dashed lines. The distinctive layers the Merensky Reef (MR), Pyroxenite Marker (PM), Main Magnetite layer (MM) and Magnetite layer 21 (M21) are marked with arrows. The thickness of the sequence varies between the eastern and western limbs. Above the UZ, felsic (Si-rich) rocks are located. The LZ is underlain by the Marginal Zone. The north to south cross-section shows the present configuration of the Bushveld layered intrusion. Modified after Eales & Cawthorn (1996) and Cawthorn & Webb (2001).

overall magma composition within the Bushveld magma chamber and forced orthopyroxene (Ca-poor pyroxene) to crystallise, resulting in the orthopyroxene-dominated, several metres thick PM (Cawthorn *et al.* 1991). The UZ can be further subdivided, based on the first appearance (first crystallisation) of new cumulus minerals within the layered sequence. The base of the UZ (subzone UZa) is defined by the appearance of cumulus Ti-magnetite (Cawthorn 2015), which is followed by the appearance of olivine (UZb) and finally apatite (UZc).

The UZ stratigraphy is dominated by gabbros with intercalated layers of anorthosite, magnetitite and nelsonite (pl. 1). While anorthosite, a plagioclase-rich rock (plagioclase: mineral series with end-member-formulas $NaAlSi_3O_8$–$CaAl_2Si_2O_8$) is economically unimportant, magnetitite (magnetite and ilmenite) and nelsonite (magnetite, ilmenite and apatite) rocks are enriched in iron, vanadium, titanium and phosphorus. This makes it important to unravel the processes involved in the formation of these layers and the resulting enrichment or depletion of economically valuable elements.

SAMPLING AND PETROGRAPHY

The exposed part of the Bushveld Complex provides only limited insights into deeper layers. For sampling of unexposed layers, drilling is necessary. The South African Geological Survey drilled three boreholes in the Bierkraal area (BK1, BK2 and BK3), north of Rustenburg intersecting the UUMZ and the PM (fig. 3). The combined cores provide a 2125-m-thick section of the intrusion. Samples from these drillcores are representative of the UUMZ in the western part of the Bushveld Complex.

The three major rock types identified in the UUMZ are gabbro, anorthosite and Fe-Ti-oxide-rich rocks (magnetitite and nelsonite). Whereas gabbros are a common rock type found in many locations and formed by slowly cooling basaltic magma, the modes of formation of the latter two rock types are still unclear for the UUMZ.

Gabbro

Gabbro is the dominant rock type in the UUMZ (pl. 2a). It is a typical rock of mafic intrusions and mainly consists of plagioclase, pyroxene and/or olivine. Distinctive for the UUMZ gabbros are their high proportions of plagioclase, magnetite and apatite. The latter mineral shows a cyclic vertical variation in abundance (Tegner *et al.* 2006). Gabbros vary markedly throughout all subdivisions in terms of mineral modes and compositions as well as textures.

Anorthosite

Minor proportions of anorthosite occur as repetitive layers within the UUMZ (pl. 2b). Compared to other rock types found in the UUMZ, they are classified as felsic rocks (rich in Si-Al). The main mineral is plagioclase with smaller proportions of mafic minerals (pyroxene and magnetite). Most anorthosite samples show slight local alteration, expressed in minerals formed after the cooling of the magma chamber (e.g., epidote, amphibole).

Magnetitite and nelsonite

Tegner *et al.* (2006) identified 26 magnetite layers and six nelsonite layers in the Bierkraal drillcores of the UUMZ, with a total thickness of 20.42 m. Magnetitite consists of massive magnetite, ilmenite and plagioclase with a few pyroxenes (pl. 2c). Magnetites from the UUMZ show a relatively high Ti concentration, ranging from 5 to 20 wt% TiO_2 (Reynolds 1985).

PLATE 1 — Photograph of the dark Main Magnetite layer overlaying a bright anorthosite layer in the Upper Zone. Photograph from Scoon & Mitchell (2012), reproduced with permission.

Nelsonites contain, in addition to the magnetitite assemblage, significant amounts of apatite.

SCIENTIFIC DEBATES AND CONTROVERSIES

Although the Bushveld Complex has been studied for more than 150 years, several recent debates and controversies emphasise the uncertainties in the understanding of this layered intrusion.

Closed- or open-system

Closed-system crystallisation means that the magma evolves and cools progressively in the magma chamber without magma eruptions or any new input of new magma, usually referred to as magma replenishment. Whether the UUMZ in the Bushveld formed in a closed system has been debated in recent years. Based on the generally consistent initial strontium isotope ratios (0.7073 ± 0.0002) of the host rocks, some researchers have concluded that the UUMZ formed by differentiation of a single magma body (Kruger *et al.* 1987, Cawthorn *et al.* 1991, Van Tongeren *et al.* 2010, Tegner *et al.* 2006). By contrast, due to an observed significant loss of incompatible elements such as K and Zr, Cawthorn & Walraven (1998) proposed that up to 40% of the magma may have been erupted. In addition, the documented compositional reversals and the obvious isotopic differences between cumulus minerals strongly indicate that the UUMZ experienced a succession of magma pulses (Ashwal *et al.* 2005, Scoon & Mitchell 2012, Tanner *et al.* 2014).

Mush emplacement versus magma recharge

The difference between the emplacement of a crystal mush and a crystal-free silicate liquid is due to the crystal load transported by the magma. In contrast to the generally assumed crystal-free liquid in many models of magma evolution (Marsh 2004, Latypov 2009), recent studies suggest that most injected magma can carry crystals, with concentration of up to 55 vol% (Marsh 2013). In addition, emplacement of plagioclase-rich mush has been proposed for the thick anorthosite layers in another layered intrusion (Stillwater Complex, Montana) (Raedeke 1982) and is also regarded as a widely accepted process to form the Proterozoic massif-type anorthosites (Ashwal 1993). Based on the magnetic susceptibility and non-cotectic proportions of plagioclase, Ashwal *et al.* (2005) and Roelofse & Ashwal (2012) suggest that this mechanism may have occurred in the UUMZ and lower Main Zone, implying the existence of a sub-Bushveld magma chamber, progressively feeding the actual Bushveld chamber with evolved magma.

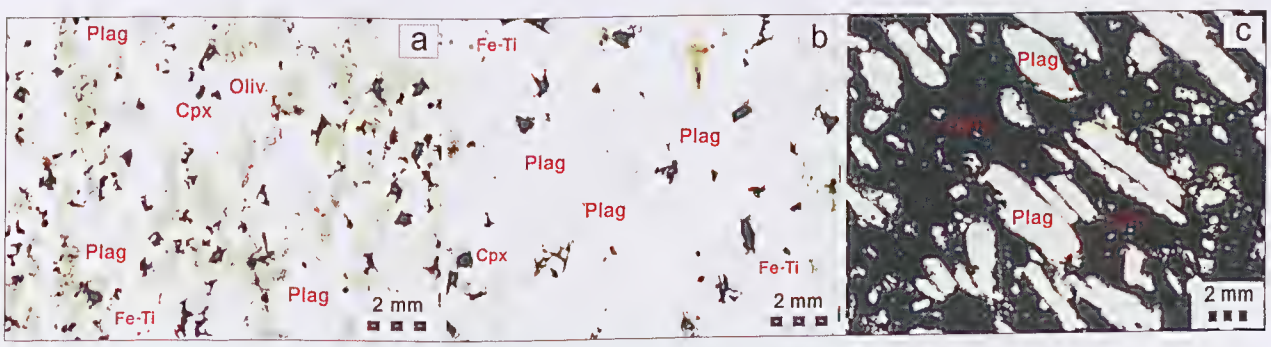


PLATE 2 — Thin section photographs of selected representative rocks from the Upper Zone. a: Gabbro, b: Anorthosite; c: Magnetitite. Plag, plagioclase; Cpx, clinopyroxene; Oliv, olivine; Fe-Ti, Fe-Ti oxides.

Liquid immiscibility

Silicate liquid immiscibility is the unmixing of two or more silicate liquids (magmas) with different compositions from a single parental magma. The unmixing of an iron-rich silicate liquid and a silica-rich silicate liquid has been identified in several locations with genetic similarities to the Bushveld Complex (e.g., Skaergaard intrusion in Greenland (Jakobsen *et al.* 2005) and Sept Iles intrusion in Canada (Namur *et al.* 2012)). In the case of the Bushveld Complex, the development of immiscible silicate liquids within the magma body has been debated and controversially interpreted. Cawthorn (2013b) challenged the occurrence of silicate liquid immiscibility, whereas von Gruenewaldt (1993) suggested that silicate liquid immiscibility might have produced the up to m-scale magnetitite and nelsonite layers. Alternatively, VanTongeren & Mathez (2012) argue that even large-scale separation of iron- and silica-rich melts at the hundreds-of-metre scale might have occurred. The latter model has been widely debated (Cawthorn 2014, VanTongeren & Mathez 2014) but consensus has not yet been reached, mainly because of the absence of any direct evidence for the existence of immiscible melts. Recently, Fischer *et al.* (2016) proposed that silicate liquid immiscibility occurred on a smaller scale (50–200 m) in the UMMZ. They suggest that sorting of immiscible melt droplets in the crystal mush possibly resulted in forming iron-rich layers within the UZ.

Link between limbs

The Bushveld Complex is exposed in three limbs, namely the western, eastern and northern limbs. Gravity models and seismic tomography have shown that the eastern and western limbs are connected at depth (Webb *et al.* 2004, Kgaswane *et al.* 2012). This is also supported by the finding of similar layers and sequences in the two limbs. Cawthorn & Webb (2001) identified six equivalent layers in the eastern and western limbs and concluded that both limbs crystallised from a single magma chamber. The presently exposed structure with two limbs is the result of isostatic depression (Cawthorn & Webb 2001).

Connection between the northern limb and the western and eastern limbs is also debated. Possibly equivalent layers were identified but no conclusive evidence could be provided (Kinnaird *et al.* 2005). Cawthorn (2015) suggested discrete evolution of the northern limb at least for the Lower and Critical Zones, based on the lack of equivalent chromitite layers in the western and eastern limbs. Ashwal *et al.* (2005) found possibly correlating layers of the Main and Upper Zone within the northern limb.

CURRENT WORK

Systematic rock and mineral chemistry study

Until now, there have been no systematic studies of whole-rock compositions in the western limb, which is an important part of the Bushveld Complex. Therefore, to better constrain the magma chamber processes associated with the UUMZ, we have collected 262 samples from the Bierkraal drillcores in the western limb of the Bushveld Complex and determined whole-rock compositions together with constituent mineral compositions and performed mineral modal proportion analysis for most samples. This extensive database will allow us to obtain precise information on the mineral modes and their variations throughout the 2-km-thick stratigraphy. In addition, the new data, together with the published V_2O_5 contents in magnetites for the same drillcores (Cawthorn & Walsh 1988), clearly indicate that the UUMZ does not correspond to a single closed system but instead exhibits several consistent compositional reversals suggesting events of magma chamber replenishment.

Melt inclusion study

During crystallisation in the magma chamber crystals can trap small amounts of the liquid from which they grow. These tiny pockets of liquid are preserved as glass and/or minerals within host crystals, while the magma evolves further. By analysing those melt inclusions we can gain information on the magma composition. These data help us to identify processes and conditions controlling the formation of the rocks and the composition of the magma prior to crystallisation.

In the UZ of the Bushveld Complex various types of inclusions can be observed in apatite. Composed of polycrystalline assemblages, such inclusions are commonly interpreted to represent crystallised equilibrium melt, trapped during the growth of apatite. They thus have the potential to record the composition of stable melts.

Recent results for Bushveld melt inclusions are presented and discussed in Fischer *et al.* (2016). They analysed 99 melt inclusions hosted in apatite of the UUMZ. Prior to analysis they re-homogenised the polycrystalline inclusions at 1100°C and a pressure of 100 MPa. Major element analyses showed a range of compositions from iron- to silica-rich. They interpret this as a result of silicate liquid immiscibility, possibly involved in forming iron-rich layers within the UZ.

Experimental study

We plan to experimentally simulate magma chamber processes to reconstruct the magmatic evolution of the UUMZ. We will use Internally Heated Pressure Vessels (IHPV, details described in Berndt *et al.* (2002)) to perform high-pressure, high-temperature experiments. Therefore, we use a synthetic magma composition contained within Pt-graphite or Au-Pd capsules, which crystallises in the course of the experiments to a mineral assemblage controlled by the applied experimental conditions. Experimental pressures and temperatures will vary within a range plausible for crustal intrusions. Run durations will range between 3–7 days to maintain equilibrium conditions between crystals and melt. Experimentally produced phases (residual magma and crystals) can be later analysed, providing important insights into phase stabilities as a function of thermodynamic conditions.

The general aim of these experiments is to match melt inclusion and residual magma compositions as well as natural and experimentally obtained crystals. This enables us to define the formation conditions (temperature, pressure, oxygen fugacity) for distinct layers, to test if silicate liquid immiscibility could have occurred during magmatic evolution, and to determine the conditions of the possible onset of the liquid unmixing process.

Bushveld Igneous Complex Drilling Project

The Bushveld Igneous Complex Drilling Project (BICDP) (Trumbull *et al.* 2015) is part of the work of the International Continental Drilling Program (ICDP), an international organisation supporting scientific continental drilling projects. Directed by two research groups from Germany (GFZ – German Research Centre for Geosciences) and South Africa (University of the Witwatersrand, Johannesburg) the BICDP started in 2014 and is currently in the planning stage. It comprises three different drill sites, one site at each limb of the intrusion (fig. 3). Combined with existing drillcores those obtained from the BICDP will cover the complete Bushveld stratigraphy in each limb. In addition to other benefits, this allows researchers to investigate vertical and lateral variations and may resolve the controversy concerning the relationships between the different limbs.

SUMMARY

The Bushveld Complex contains major resources of PGEs, iron, titanium, vanadium and other elements. With increasing demand for these elements, the Bushveld deposits are of critical economic interest. The distribution of valuable elements follows the characteristics of a layered intrusion in that certain elements are concentrated at distinct levels of the intrusion. However, the actual processes involved in the formation of these layers are still controversially debated. We have produced a systematic dataset for whole rock, mineral and melt inclusion compositions for the upper part of the Bushveld Complex and will complement these data with an experimental study of magma crystallisation. This will allow us to approach recent questions with new arguments.

ACKNOWLEDGEMENTS

This project was supported by a DAAD-Doktorandenstipendium for L.A. Fischer. O. Namur, B. Charlier, F. Holtz and A. Husen are thanked for discussions and their comments. The comments of two anonymous reviewers improved the quality of this paper.

REFERENCES

Ashwal, L. 1993: *Anorthosites* Springer, Heidelberg: 422 pp.

Ashwal, L.D., Webb, S.J. & Knoper, M.W. 2005: Magmatic stratigraphy in the Bushveld Northern Lobe: Continuous geophysical and mineralogical data from the 2950 m Bellevue drillcore. *South African Journal of Geology* **108**: 199–232.

Barnes, S-J. & Maier, W.D. 2002: Platinum-group element distributions in the Rustenberg Layered Suite of the Bushveld Complex, South Africa. *In* Cabri L.J. (ed): *The Geology, Geochemistry, Mineralogy and Mineral Beneficiation of Platinum-Group Elements.* Canadian Institute of Mining, Metallurgy and Petroleum, Special Volume 54: 431–458.

Barnes, S-J., Maier, W.D. & Curl, E.A. 2010: Composition of the Marginal Rocks and Sills of the Rustenburg Layered Suite, Bushveld Complex, South Africa: Implications for the Formation of the Platinum-Group Element Deposits. *Economic Geology* **105**: 1491–1511.

Berndt, J., Liebske, C., Holtz, F., Freise, M., Nowak, M., Ziegenbein, D., Hurkuck, W. & Koepke, J. 2002: A combined rapid-quench and H_2-membrane setup for internally heated pressure vessels: Description and application for water solubility in basaltic melts. *American Mineralogist* **87**: 1717–1726.

Campbell, I.H. 1978: Some problems with the cumulus theory. *Lithos* **11**: 311–323.

Cawthorn, R.G. & Walraven, F. 1998: Emplacement and Crystallization Time for the Bushveld Complex. *Journal of Petrology* **39**: 1669–1687.

Cawthorn, R.G. & Walsh, K.L. 1988: The use of phosphorus contents in yielding estimates of the proportion of trapped liquid in cumulates of the Upper Zone of the Bushveld Complex. *Mineralogical Magazine* **52**: 81–89.

Cawthorn, R.G. & Webb, S.J. 2001: Connectivity between the western and eastern limbs of the Bushveld complex. *Tectonophysics* **330**: 195–209.

Cawthorn, R.G. 2013a: The Residual or Roof Zone of the Bushveld Complex, South Africa. *Journal of Petrology* **54**: 1875–1900.

Cawthorn, R.G. 2013b: Rare earth element abundances in apatite in the Bushveld Complex – A consequence of the trapped liquid shift effect. *Geology* **41**: 603–606.

Cawthorn, R.G. 2014: Rare earth element abundances in apatite in the Bushveld Complex - A consequence of the trapped liquid shift effect: REPLY. *Geology* **42**: e319–e319.

Cawthorn, R.G. 2015: The Bushveld Complex, South Africa. *In* Charlier, B., Namur, O., Latypov, R. & Tegner, C. (eds): *Layered Intrusions.* Springer, Netherlands: 517–587.

Cawthorn, R.G., Meyer, P.S. & Kruger, F.J. 1991: Major addition of magma at the pyroxenite marker in the western bushveld complex, South Africa. *Journal of Petrology* **32**: 739–763.

Davies, G., Cawthorn, R.G., Barton, J.M. & Morton, M. 1980: Parental magma to the Bushveld complex. *Nature* **287**: 33–35.

Devouard, B., Pósfai,M., Hua, X., Bazylinski, D.A., Frankel, R.B. & Buseck, P.R. 1998: Magnetite from magnetotactic bacteria: Size distributions and twinning. *American Mineralogist* **83**: 1387–1398.

Eales, H.V. & Cawthorn, R.G. 1996: The Bushveld Complex. *In* Cawthorn, R.G. (ed): *Layered Intrusions.* Elsevier, Amsterdam: 181–229.

Fischer, L.A., Wang, M., Charlier, B., Namur, O., Roberts, R.J., Veksler, I. V., Cawthorn, R.G. & Holtz, F. 2016: Immiscible iron-and silica-rich liquids in the Upper Zone of the Bushveld Complex. *Earth and Planetary Science Letters* **443**: 108–117.

Fletcher, W.K. & Wolcott, J. 1991: Transport of magnetite and gold in Harris Creek, British Columbia, and implications for exploration. *Journal of Geochemical Exploration* **41**: 253–274.

Garzanti, E., Andò, S., France-Lanord, C., Vezzoli, G., Censi, P., Galy, V. & Najman, Y. 2010: Mineralogical and chemical variability of fluvial sediments 1. Bedload sand (Ganga–Brahmaputra, Bangladesh). *Earth and Planetary Science Letters* **299**: 368–381.

Green, T.H. & Watson, E.B. 1982: Crystallization of apatite in natural magmas under high pressure, hydrous conditions, with particular reference to "Orogenic" rock series. *Contributions to Mineralogy and Petrology* **79**: 96–105.

Hirschler, A., Lucas, J. & Hubert, J-C. 1990: Bacterial involvement in apatite genesis. *FEMS Microbiology Ecology* **73**: 211–220.

Jakobsen, J.K., Veksler, I.V., Tegner, C. & Brooks, C.K. 2005 Immiscible iron- and silica-rich melts in basalt petrogenesis documented in the Skaergaard intrusion. *Geology* **33**: 885.

Kgaswane, E.M., Nyblade, A.A., Durrheim, R.J., Julià, J., Dirks, P.H.G.M. & Webb, S.J. 2012: Shear wave velocity structure of the Bushveld Complex, South Africa. *Tectonophysics* **554–557**: 83–104.

Kinnaird, J.A., Hutchinson, D., Schurmann, L., Nex, P.A.M. & de Lange, R. 2005: Petrology and mineralisation of the southern Platreef: Northern limb of the Bushveld Complex, South Africa. *Mineralium Deposita* **40**: 576–597.

Kruger, F.J., Cawthorn, R.G. & Walsh, K.L. 1987: Strontium isotopic evidence against magma addition in the Upper Zone of the Bushveld Complex. *Earth and Planetary Science Letters* **84**: 51–58.

Latypov, R. 2009: Testing the validity of the petrological hypothesis "no phenocrysts, no post-emplacement differentiation". *Journal of Petrology* **50**: 1047–1069.

Marsh, B. 2004: A magmatic mush column rosetta stone: The McMurdo Dry Valleys of Antarctica. *Eos, Transactions American Geophysical Union* **85**: 497.

Marsh, B.D. 2013: On some fundamentals of igneous petrology. *Contributions to Mineralogy and Petrology* **166**: 665–690.

Namur, O., Abily, B., Boudreau, A.E., Blanchette, F., Bush, J.W.M., Ceuleneer, G., Charlier, B., Donaldson, C.H., Duchesne, J-C., Higgin, M.D., Morata, D., Nielsen, T.F.D., O'Driscoll, B., Pang, K.N., Peacock, T., Spandler, C.J., Toramaru, A. & Veksler, I.V. 2015: Igneous Layering in Basaltic Magma Chambers. *In* Charlier, B., Namur, O., Latypov, R. & Tegner, C. (eds): *Layered Intrusions.* Springer, Netherlands: 75–152.

Namur, O., Charlier, B. & Holness, M.B. 2012: Dual origin of Fe-Ti-P gabbros by immiscibility and fractional crystallization of evolved tholeiitic basalts in the Sept Iles layered intrusion. *Lithos* **154**: 100–114.

Namur, O., Charlier, B., Pirard, C., Hermann, J., Liégeois, J-P. & Vander Auwera, J. 2011: Anorthosite formation by plagioclase flotation in ferrobasalt and implications for the lunar crust. *Geochimica et Cosmochimica Acta* **75**: 4998–5018.

Nystrom, J.O. & Henriquez, F. 1994: Magmatic features of iron ores of the Kiruna type in Chile and Sweden: ore textures and magnetite geochemistry. *Economic Geology* **89**: 820–839.

Raedeke, L.D. 1982: *Petrogenesis of the Stillwater Complex* Unpublished PhD thesis, University of Washington.

Reynolds, I.M. 1985: Contrasted mineralogy and textural relationships in the uppermost titaniferous magnetite layers of the Bushveld complex in the Bierkraal area north of Rustenburg. *Economic Geology* **80**: 1027–1048.

Roelofse, F. & Ashwal, L.D. 2012: The Lower Main Zone in the Northern Limb of the Bushveld Complex - a >1·3km Thick Sequence of Intruded and Variably Contaminated Crystal Mushes. *Journal of Petrology* **53**: 1449–1476.

Scoon, R.N. & Mitchell, A.A. 2012: The upper zone of the bushveld complex at Roossenekal, South Africa: Geochemical stratigraphy and evidence of multiple episodes of magma replenishment. *South African Journal of Geology* **115**: 515–534.

Song, X-Y., Qi, H-W., Hu, R-Z., Chen, L-M., Yu, S-Y. & Zhang, J-F. 2013: Formation of thick stratiform Fe-Ti oxide layers in layered intrusion and frequent replenishment of fractionated mafic magma: Evidence from the Panzhihua intrusion, SW China. *Geochemistry, Geophysics, Geosystems* **14**: 712–732.

Tanner, D., Mavrogenes, J.A., Arculus, R.J. & Jenner, F.E. 2014: Trace Element Stratigraphy of the Bellevue Core, Northern Bushveld: Multiple Magma Injections Obscured by Diffusive Processes. *Journal of Petrology* **55**: 859–882.

Tegner, C., Cawthorn, R.G. & Kruger, F.J. 2006: Cyclicity in the Main and Upper Zones of the Bushveld Complex, South Africa: Crystallization from a Zoned Magma Sheet. *Journal of Petrology* **47**: 2257–2279.

Trumbull, R.B., Ashwal, L.D., Webb, S.J. & Veksler, I.V. 2015: Drilling through the largest magma chamber on Earth: Bushveld Igneous Complex Drilling Project (BICDP). *Scientific Drilling* **19**: 33–37.

U.S. Geological Survey 2015: *Mineral Commodity Summaries* U.S. Geological Survey.

VanTongeren, J.A. & Mathez, E.A. 2012: Large-scale liquid immiscibility at the top of the Bushveld Complex, South Africa. *Geology* **40**: 491–494.

VanTongeren, J.A. & Mathez, E.A. 2014: Rare earth element abundances in apatite in the Bushveld Complex—A consequence of the trapped liquid shift effect: Comment. *Geology* **42**: e318.

VanTongeren, J.A., Mathez, E.A. & Kelemen, P.B. 2010: A felsic end to Bushveld differentiation. *Journal of Petrology* **51**: 1891–1912.

von Gruenewaldt, G. 1993: Ilmenite-apatite enrichments in the upper zone of the Bushveld complex: a major titanium-rock phosphate resource. *International Geology Review* **35**: 987–1000.

Wager, L.R. & Brown, G.M. 1968: *Layered Igneous Rocks.* Oliver and Boyd, London: 588 pp.

Webb, S.J., Cawthorn, R.G., Nguuri, T. & James, D. 2004: Gravity modeling Bushveld complex connectivity supported by Southern African Seismic Experiment results. *South African Journal of Geology* **107**: 207–218.

Zeh, A., Ovtcharova, M., Wilson, A.H. & Schaltegger, U. 2015: The Bushveld Complex was emplaced and cooled in less than one million years – results of zirconology, and geotectonic implications. *Earth and Planetary Science Letters* **418**: 103–114.

(Accepted 3 May 2016)

HANS HERMANN BEHR (1818–1904): BOTANIST, ENTOMOLOGIST, ANTHROPOLOGIST, HUMORIST AND DANGEROUS?

by Allan H. Bretag

(with one text-figure and six plates)

Bretag, A.H. 2016 (31:viii): Hans Hermann Behr (1818–1904): botanist, entomologist, anthropologist, humorist and dangerous? *Papers and Proceedings of the Royal Society of Tasmania* 150(1): 23–30. ISSN 0080-4703. School of Pharmacy and Medical Sciences, University of South Australia, Adelaide, SA 5000, Australia. Email: bretagah@iinet.net.au

Hans Hermann Behr arrived in Adelaide in late 1844 as a newly-graduated doctor interested more in botany, entomology and anthropology. After just one year, he returned to Germany with prolific samples and notes. He returned to Adelaide towards the end of 1848, again exploring and collecting extensively. Within a year he left for the Philippines and after another year had arrived in San Francisco where he firmly established his international reputation.

Key Words: Hans Hermann Behr, South Australia, California, botany, entomology, humour.

INTRODUCTION

Hans Hermann Behr (pl. 1) was born on 18 August 1818 at Cöthen in the Duchy of Anhalt-Cöthen. After schooling in Cöthen, he studied in Halle and Würzburg before being awarded his medical doctorate from the Friedrich Wilhelm University of Berlin (now the Humboldt University) in 1843 (Kraehenbuehl 1981). Motivated by his interests other than medicine and encouraged by mentors and friends including Alexander von Humboldt and Karl Ritter, he soon left for the new colony of South Australia and arrived in Adelaide in September 1844 (Kraehenbuehl 1981). Although newly graduated as a doctor, he was, apparently, interested only in collecting plants and insects and studying the behaviours and interactions of the colonists and Aborigines. He left Adelaide in October 1845, returning to Germany by mid-1846, having made prolific collections and observations on short explorations in the ranges and river flats to the immediate north and east of Adelaide (Kraehenbuehl 1981). These materials were quickly assembled for publication but, disenchanted with the social situation and his personal prospects in Cöthen, he returned to Adelaide towards the end of 1848 (Garstenauer 2015). He again collected extensively. Within a year, however, Behr had left for the Philippines (Kraehenbuehl 1981) and after another year or so had arrived in San Francisco (Behr 1891) where he firmly established his international reputation (Legge 1953).

PLATE 1 — Hans Hermann Behr in about 1883. Image courtesy of the University and Jepson Herbaria Archives, University of California, Berkeley.

DR HANS HERMANN BEHR: A BRIEF BIOGRAPHY

Unlike Hans Hermann Behr, who grew up in Cöthen in the Duchy of Anhalt-Cöthen, I was raised in the Zoological Park (at the time, my parents' farm) at Monarto, South Australia, located about midway between Mount Barker and Murray Bridge, 70 km southeast of Adelaide (fig. 1). There, as a child, I first came across Behr when my grandmother took me picking wildflowers. Strictly speaking, my introduction was to Behr's Pink Velvet Bush, *Lasiopetalum behrii* F. Muell., a shy, flowering shrub growing on the property; shy because its beautiful pink-faced flowers hang down, unexceptional, until lifted into view. Plate 2 shows a photograph of Behr's Pink Velvet Bush taken in 1973 in what is now the Bretag's Scrub conservation area within the Monarto Zoological

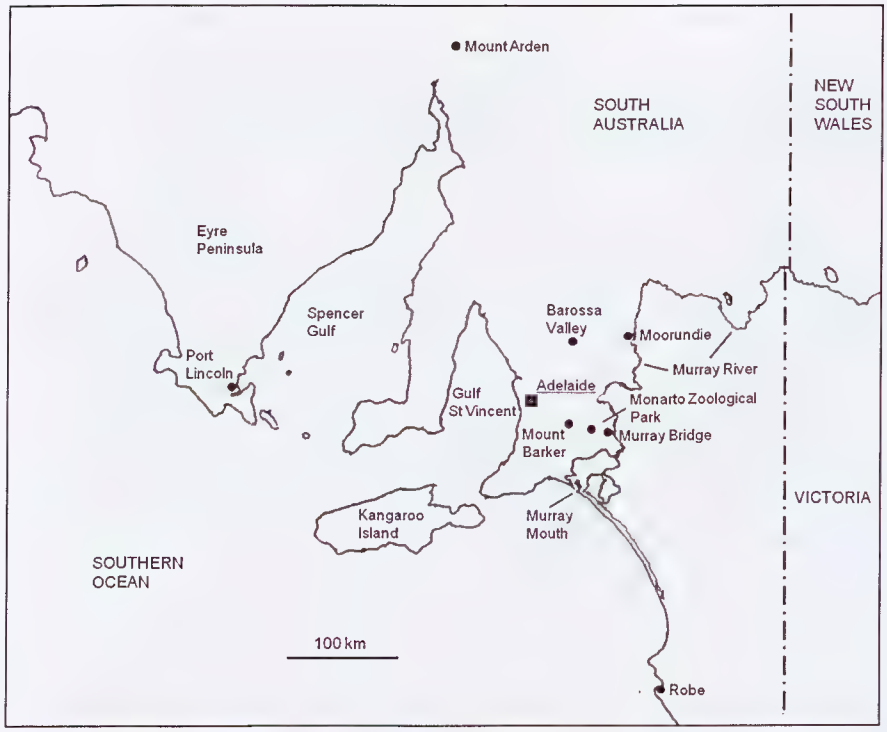


FIG. 1 — Map of southern South Australia showing places and regions where Hans Hermann Behr, Ferdinand Mueller and other German naturalists mentioned in the text, as well as, George French Angas explored and collected specimens.

PLATE 2 — Behr's Pink Velvet Bush, *Lasiopetalum behrii* F. Muell. photographed by Allan Bretag in 1973 in Bretag's Scrub (now part of the Monarto Zoological Park), Monarto South, South Australia.

Park. According to Ferdinand Mueller's formal description, this plant was found "In the Mallee Scrub on the Murray River and St. Vincent's Gulf, where it was first observed by Dr. H. Behr" (Mueller 1855, p. 36).

After arriving in South Australia on the *George Washington* on 12 September 1844, Behr centred his activities in and near the Barossa Valley and its prominent German settlement at Tanunda (especially at nearby Bethanien) (Kraehenbuehl 1981). From there his exploratory and collecting excursions took him generally within 100 km to the north and east of Adelaide, between Gulf St Vincent and the Murray River. He collected plants as early as November/December 1844 from the upper regions of the Torrens and Onkaparinga rivers and from the Mount Barker region, near Hahndorf (Schlechtendal 1847) and reported climbing Mount Barker (fig. 1), southeast of Adelaide (Behr 1847). Exactly how far south he explored is uncertain although some of his accounts suggest that he could have visited the area near the Murray mouth (fig. 1) (Behr 1848a, b).

In two anthropological papers that he presented to the Berlin Geographical Society, for example, he describes his interactions with Aborigines and observations on their corroborees, their language and their beliefs (Behr 1848a, b). Unlike many general views and opinions from his time, he considered their corroborees to be akin to church services and their language to be complex, but he was critical of their morality (there is no right or wrong, only instinctive reactions to immediate circumstances with no underlying moral code of behaviour). With a certain amount of naïve, Eurocentric arrogance, he placed them at the lowest level of human development, although he did attribute this to their geographical situation. On the other hand, he conceded that the Aborigines living in the region of the Murray mouth had a religious belief in a higher being and in a life after

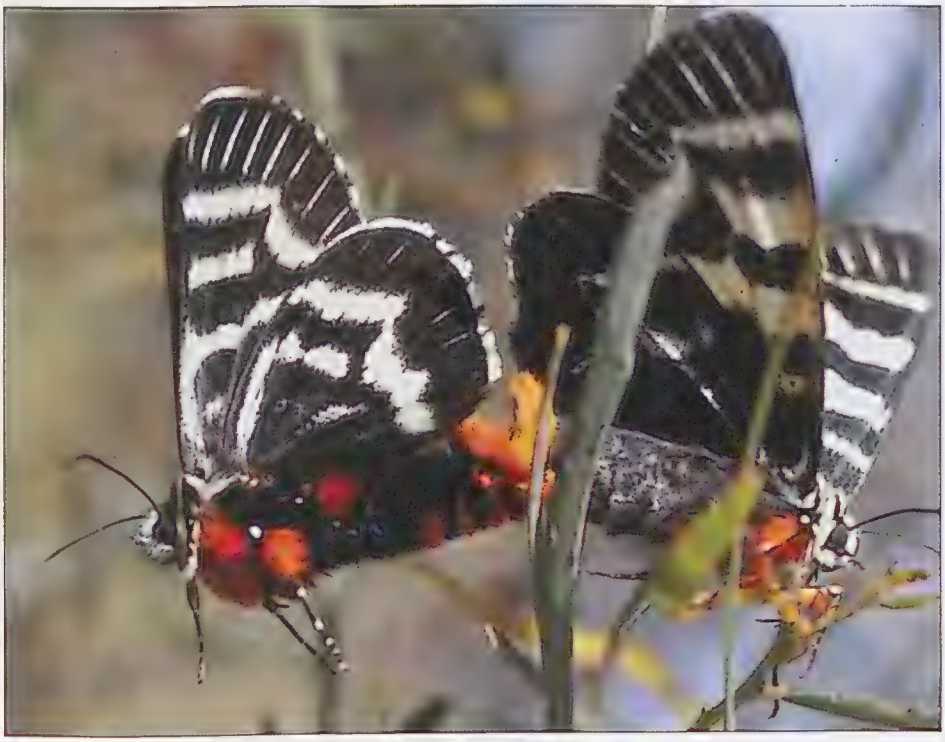


PLATE 3 — Pair of Mistletoe Moths, *Comocrus behri* (Angas, 1847), mating. Image: courtesy of Eileen Collins, Chiltern, Victoria.

death. Whether this came from personal observations of the southern coastal Aborigines, or not, is uncertain. What is certain, however, is that on 9 October 1845, Behr left Adelaide on board the *Heerjeebhoy Rustomjee Patel* to make his way home to Cöthen via Java and the Cape of Good Hope (Kraehenbuehl 1981).

During this first visit to Australia he must have met George French Angas, son of George Fife Angas who played a large role in the founding of South Australia as a colony (Anon 2016a). Behr collected on and around land owned by George Fife Angas at Angas Park (present-day Nuriootpa) and Angastown (present-day Angaston) in the Barossa Valley (Schlechtendal 1847). Both Behr and George French Angas were in South Australia in the first half of 1845. Angas, himself a naturalist, an explorer and also an artist, seems to have been sufficiently impressed by Behr to have awarded him among the first published honours in a species name for the strikingly beautiful Mistletoe Moth, *Comocrus behri* (Angas, 1847), originally illustrated and named *Agarista behri* by Angas (pl. 3) (Angas 1847). In the legend to Plate XLVIII of his folio, *South Australia Illustrated*, Angas acknowledged the contribution to entomological science made by Behr and a number of other residents "in the Province of South Australia for the addition of many new species" (Angas 1847).

From 1847 onwards, Behr, then back in Cöthen, together with the German experts to whom he had passed his South Australian specimens, also began to publish formal descriptions of many of the new species of plants and insects he had brought back with him. Examples come from the approximately 140 specimens of Lepidoptera that Behr gave to Johann Christoph Friedrich Klug in Berlin (Klug 1850), from the unknown number of beetles left with Ernst Friedrich Germar in Halle and from well over 200 plants provided to Diederich Franz Leonhard von Schlechtendal also in Halle (Schlechtendal 1847, 1848). Some of these also honoured Behr.

As new Lepidopteran species, Klug described the Orange Sun Moth, *Synemon nais* Klug, 1850, and the Pale Sun Moth, *Synemon selene* Klug, 1850. Although Klug's paper only appeared in print in 1850 it was read before the Academy of Sciences in Berlin in May 1848 and was published as part of the Proceedings of the Academy from 1848 (Klug 1850). Interestingly, the Pale Sun Moth was later described as *Synemon adelaida* Swinhoe, 1892 (Swinhoe 1892), geographically appropriate but not accepted due to Klug's precedence.

Of the plant specimens treated by Schlechtendal, about 70 were considered to be new species, for example, *Prostanthera behriana* Schltdl. (Schlechtendal 1847). This pale flowering Downy Mintbush is somewhat similar to the extremely rare Monarto Mintbush, the bright-purple flowering *Prostanthera eurybioides* F. Muell. illustrated here (pl. 4).

The Darkling Beetle (pl. 5), *Cardiothorax behri* (Germar, 1848) is one of the many insect specimens collected by Behr and was formally described as "*Prosodes? Behrii*" by Germar (1848).

By early 1848, Behr had developed a deep sympathy for, and was beginning to become involved in, the revolutionary movements for political and social reform sweeping Europe. His employment prospects as a young doctor were diminishing in Cöthen, perhaps partly due to his increasingly radical views and partly due to growing competition from Christian Friedrich Samuel Hahnemann's "Homeopathy" that had been uniquely and especially nurtured and protected in Cöthen by the Duke Friedrich Ferdinand of Anhalt-Cöthen (Garstenauer 2015). Hahnemann had termed conventional medicine "Allopathy"

PLATE 4 — Brightly coloured flowers of the extremely rare Monarto Mintbush, *Prostanthera eurybioides* F. Muell. Image courtesy of John Boland, Adelaide, South Australia.

and warned against its dangers. In any case, by May 1848 Behr was on his way back to Adelaide.

Meanwhile, on 15 December 1847, Dr Ferdinand Mueller and Ferdinand Osswald (both pharmaceutical chemists with particular interests in botany) had arrived in Adelaide on the *Hermann von Beckerath* (Anon 1847) whereupon Mueller undertook his first employment in the German chemist shop of Büttner and Heuzenroeder, Chemists and Druggists (Anon 1896) (in operation from January 1846 until the dissolution of their partnership in January 1849) (Anon 1849a). Joseph Hieronymus Moritz Heuzenroeder had arrived on the *Heerjeebhoy Rustomjee Patel* on 18 September 1845 (Anon 1845) and was himself an avid collector of the plants and insects of the new colony (Jones 2011). As mentioned above, it was just three weeks later that Behr ended his first stay in South Australia, leaving on the same ship.

In the year leading up to Behr's arrival on his second visit to South Australia (in November 1848), Osswald was collecting around the Barossa Valley and in the South East district of the state, near Robe (Kraehenbuehl 1981). Osswald seems to have taken over the German chemist shop in Rundle Street in 1849 because Dr William Hillebrand (see below) advertised on 21 April 1849 that he would consult from there "every morning till 11 o'clock" (Anon 1849b).

Ferdinand Mueller, too, was collecting and exploring further north during 1848, up to Mount Arden in the Flinders Ranges area (fig. 1). He had also purchased a small property at Bugle Ranges south of Mount Barker (fig. 1), some 30 km southeast of Adelaide (Anon 1896). It is likely that at about this time Mueller collected, or was supplied with, a specimen of the very rare Monarto Mintbush, *Prostanthera eurybioides* (pl. 4). Because of its extremely restricted geographical range, there is a very good chance it was found in the Mallee Scrub within, or neighbouring, the Monarto Zoological Park (in accord with Mueller's 1855 description, illustrated and mentioned above) (Mueller 1855).

Back in South Australia again, arriving on the *Victoria* on 6 November 1848, Behr once more collected around the Barossa Valley and east to the River Murray (Kraehenbuehl 1981). An eloquent account of his observations on an excursion made to "Maronde" [= Moorundie], south of the present-day Blanchetown, has been published in translation (Kraehenbuehl 1981). The recipients of Behr's 1848–49 collections are uncertain although, in a note relating to a letter sent by Behr from Manila in December 1849, it is suggested that his plant specimens may have been sent to William Jackson Hooker at Kew in the United Kingdom (Anon 1850).

Dr Wilhelm (William) Hillebrand (physician) and Carl Wilhelmi (seedsman), fellow Germans with a zeal for botanical collecting, arrived in Adelaide in March 1849 on the *Godeffroy* (see below), Hillebrand subsequently exploring the southern Mount Lofty Ranges to Lake Alexandrina. Wilhelmi covered much the same area as that investigated by Hillebrand and Behr before turning his attention west to the Port Lincoln area on Eyre Peninsula and then to the South East district of the state (Jones 2011, Anon 2016b).

It seems most likely that these Germans and others already in South Australia (Jones 2011) would have met and known each other, and even explored and collected together at times, although evidence is scant (Kraehenbuehl 1981) and at times unreliable. For example, Meier (Meier 2005a, p. 8) has written:

> *When the Godeffroy made Port Phillip, South Australia [actually, Port Phillip is in Victoria], on February 10, 1849, she could boast about having sailed from Plymouth to Australia in ninety-four days. Hardly off*

PLATE 5 — Darkling Beetle, *Cardiothorax behri* (Germar, 1848). Image courtesy H. De Graaf, (SARDI), Adelaide, South Australia.

> *the boat and still overwhelmed by their impressions of the new continent, Hillebrand and fellow botanists Otto Boesewetter and J.F.C. Wilhelmi, who had traveled with him from Germany, met in Ferdinand Mueller's Melbourne home … Mueller introduced him [Hillebrand] to Hans Hermann Behr.*

Actually, shortly after arriving at Port Phillip, the *Godeffroy* sailed on to Port Adelaide, South Australia, arriving on 1 March (Anon 1849c). While there is no evidence that Boesewetter travelled on to Port Adelaide, Hillebrand and Wilhelmi definitely did (Anon 1849c) and, actually, Mueller's home at the time was in Adelaide, South Australia (Anon 1896), and not Melbourne, Victoria, so if these botanists met immediately after their arrival, it would have been in Adelaide.

Behr and Hillebrand left Adelaide together in spring 1849 travelling on to the Philippines (Kraehenbuehl 1981, Anon 1850). It is uncertain exactly when and how they left Adelaide, but one possibility is that they sailed on the *Wilhelmine Marie* that left Port Adelaide on about 22 September 1849 bound for Manila (Anon 1849d). They had arrived in Manila by 12 December 1849 when they both applied for physician's licences (Garstenauer, W., University of Vienna, pers. comm. 2015). Neither Behr nor Hillebrand remained long in the Philippines. Behr's departure date from Manila is unknown but by late September 1850 he was in San Francisco (Behr 1891). Hillebrand left on 11 September 1850 on the *Naumkeang*, arrived in San Francisco on 29 November (Meier 2005b) and by 22 December he had reached Honolulu (Greer 1969). No plant or insect collections made by Behr or Hillebrand in the Philippines are known to exist (Krahenbuehl 1981).

In California, Behr became famous in several fields, most of which were not well-rewarded financially so that he was obliged to practise as a physician. Soon after his arrival there were major outbreaks of cholera in San Francisco and Sacramento. Not much later, a notorious gang of Australian ex-convicts, the "Sydney Ducks", were accused of robbery, extortion and widespread arson. A store in central San Francisco was set on fire in mid-1851 leading to some 2000 surrounding buildings being destroyed in the resultant conflagration (Anon 2016c). In that year Behr became a member of the San Francisco Vigilance Committee, outside the law, that hanged several of the criminals and drove the remnants out of town. His scientific training and expertise soon led him to join the fledgling California Academy of Sciences (1854) (Gutzkow *et al.* 1905), being made curator of the Entomology Department for varying periods beginning in 1862 (Anon 2016d). He was later appointed as the Foundation Professor of Botany at the California College of Pharmacy (1872) (Legge 1953) and was elected to membership of the Bohemian Club of San Francisco (1873) (Legge 1953).

By 1882 his collection of Lepidoptera had grown to nearly 20 000 specimens through his own long-term and ardent collecting and international exchanges (Anon 1882). On these, he had written numerous papers (the Royal Society of London's Catalogue of Scientific Papers shows 10 published between 1863 and 1870, and see also Legge (1953)) and had himself formally described many new species (e.g., Behr 1870). Presumably, his collection had grown considerably larger by the time of his death in 1904. Unfortunately, this outstanding collection and Behr's personal papers were all lost, with a single known exception, along with most of the California Academy of Sciences Museum's mammal, bird, insect and plant specimens in the disastrous fire following the 1906 San Francisco earthquake (Leviton & Aldritch 1997, Moran 2013). Rediscovered in 2013, the single surviving book that had originally belonged to Behr was

a folio of ornithological illustrations which, according to its inscription, he had presented to the museum director, Leverett M. Loomis, in 1901. The first plate in the folio retains the handwritten signature, "Property of H.H. Behr Dr" (Moran 2013).

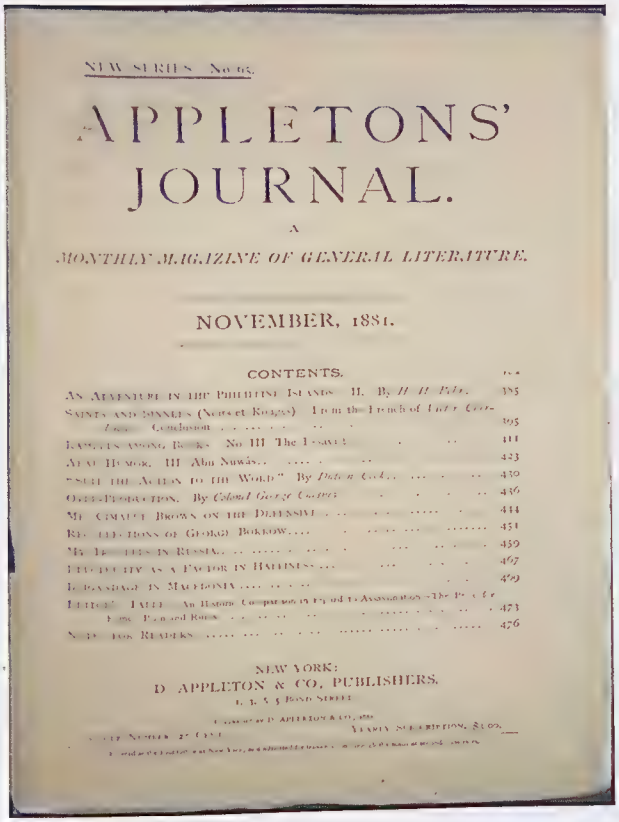
Apart from his renowned scientific works, Behr was also an accomplished writer of fiction in English and German, often humorous, from novels, short stories and verse to "jinks", these last being short speeches to the San Francisco Bohemian Club that were collected and published posthumously as *Hoot of the Owl* (Behr 1904). In one of the many memorable examples of these, he writes that he was admonished to be virtuous and become happy by his aunt who was "an elderly lady, not exactly prepossessing in her exterior, but shockingly virtuous and as unmarried as possible". She drank valerian tea with a dash of ether in it, wore green spectacles, "always felt miserable and respectable, and between asafoetida and valerian led a most unhappy life". Behr, nevertheless, decided "to give virtue a fair shake" and subsequently tried many virtues in moderation but concluded that the happiest moment of his life was when he "dropped virtue altogether". In another instance, he says he was asked to make a presentation to his fellow Bohemians on ethnology, but being unsure of whether they meant entomology, he wrote:

> *At first I intended to follow the custom of my fellow-scientists – that is, to compile an ethnological or entomological paper of plagiarisms, in which only the errors are my own; but, on more mature reflection, I thought, as Alexander von Humboldt is dead …, I would not run the slightest risk to be discovered in drawing from my own bold and lively imagination.* (Behr 1904, pp. 101–102)

Under the pseudonym, "Ati Kambang", he also wrote a three-volume novel largely set in South Australia, *Auf fremder Erde* (Kambang 1864), utilising humour in describing the behaviours and interactions between the various ethnic immigrant groups and the Aborigines. He provides astute observations of these people's religions and superstitions in the light of the scientific knowledge of the time (Garstenauer 2013). Another novel, *Dritte Söhne*, about California, was published in instalments in a German-language Californian newspaper, but apparently only fragments remain (Garstenauer, W., University of Vienna, pers. comm. 2015).

In the story, "An Adventure in the Philippine Islands", published in the October and November 1881 issues of the New York Literary Magazine, *Appletons' Journal* (pl. 6) (Behr 1881a, b), he wrote of himself (possibly with at least a grain of autobiographical truth), "I was young, a socialist, and emancipation-mad in different directions", and, "In the glorious year of 1848 I had been guilty of all sorts of misdemeanours, [and] looked upon myself as a very dangerous kind of person" (Garstenauer 2013, pp. 56–63, Behr 1881a, p. 339).

Behr has been described as an amiable fellow and a genial host but also as rather weird and hot-tempered (Kraehenbuehl 1981, Garstenauer 2015, Meier 2005b). Apart, perhaps, from some early flirtations with radicalism and his later membership of the San Francisco Vigilance Committee, none of this suggests that Behr really was a dangerous person. His observations of the devastating effects of human activity in building cities and expanding agriculture (Behr 1847) and of the inadvertent introduction of invasive species such as Milk Thistles *Silybum marianum* (L.) Gaertn. and Water Buttons *Cotula coronopifolia* L. in both South Australia and California (Behr 1891), indicate that he was deeply aware of ecological and environmental damage. Nevertheless, he himself seems to have been involved in the introduction of Australasian White Mangroves *Avicennia marina* subsp. *australasica* (Walp.) J.Everett (Legge 1953) and various Eucalypts (Santos 1997) to California. Definitely not benign, the subsequent weed-like proliferation of these species has proven that this was probably his most dangerous action.


NEW SERIES No. 65.

APPLETONS' JOURNAL.

A

MONTHLY MAGAZINE OF GENERAL LITERATURE.

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NEW YORK:
D. APPLETON & CO., PUBLISHERS,
1, 3, & 5 BOND STREET.

PLATE 6 — Cover of Appletons' Journal for November 1881with its Contents showing "An Adventure in the Philippine Islands II" by H.H. Behr.

CONCLUSIONS

Overall, Behr made an exceptional, but no longer sufficiently-recognised, contribution to the early knowledge of South Australian and Californian plant and insect species. Although he was an accomplished linguist, perhaps due to the short time that he spent in South Australia, his interactions with, and observations of, the local Aborigines were hindered

by communication difficulties making his accounts of them seem somewhat amateurish. His best contributions to ethnology came in his depictions of immigrant and indigenous South Australians in his humorous novel, *Auf fremder Erde*. Behr's later academic involvement with the California Academy of Sciences and the California College of Pharmacy was outstanding. His *alma mater*, the Friedrich Wilhelm University of Berlin, recognised all of this when it honoured and feted him on the occasion of his 80th birthday with the award of the honorary degree of "Doctor Honoris Causa" on 18 August 1898 (Anon 1904).

ACKNOWLEDGEMENTS

I particularly want to acknowledge the late Margaret Kenny of the South Australian Museum who formally introduced me to *Lasiopetalum behrii* in 1973, thereby triggering my subsequent search for information about Behr. Darrell Kraehenbuehl's detailed account of Behr's two visits to South Australia was particularly informative, helping me to track down much of Behr's early botanical, entomological and anthropological work. I have also been greatly assisted by Werner Garstenauer of the University of Vienna with respect to Behr's political views, his travels to and from the Philippines and his fictional and ethnographic publications.

REFERENCES

Angas, G.F. 1847: *South Australia Illustrated.* Thomas McLean, London: Part 7, plate 37.

Anon. 1845: *South Australian Register,* 23 September, p. 2.

Anon. 1847: *South Australian Register,* 18 December, p. 4.

Anon. 1849a: *South Australian Register,* 3 January, p. 2.

Anon. 1849b: *Adelaide Observer,* 21 April, p. 1.

Anon. 1849c: *South Australian Register,* 3 March, p. 4.

Anon. 1849d: *South Australian Register,* 22 September, p. 4.

Anon. 1850: Reisende. *Botanische Zeitung* **8**: 335.

Anon. 1882: 'A Fine Collection of Butterflies', *New York Times,* 25 December 1882 [Headline].

Anon. 1896: *South Australian Register,* 12 October, p. 7.

Anon. 1904: Dr. Hans Herman Behr. *Entomological News* **15**: 142–144.

Anon. 2016a: *George French Angas,* https://en.wikipedia.org/wiki/George_French_Angas (accessed 25 January 2016).

Anon. 2016b: *Council of Heads of Australasian Herbaria: Biographical Notes,* https://www.anbg.gov.au/biography/wilhelmi-carl.html (accessed 25 January 2016).

Anon. 2016c: *Timeline San Francisco to 1892,* http://www.timelines.ws/cities/SF_A_1892.HTML (accessed 25 January 2016).

Anon. 2016d: California Academy of Sciences: Entomology Collection, http://www.calacademy.org/scientists/entomology-collection (accessed 25 January 2016).

Behr, H.H. 1847: Ueber die Verhältnisse der südaustralischen Flor im Allgemeinen. *Linnaea* **20**: 545–558.

Behr, H.H. 1848a: Über die Urbewohner von Adelaide in Süd-Australien nach eigenen Anschauungen,während seines dortigen Aufenthalts. *Monatsberichte über die Verhandlungen der Gesellschaft für Erdkunde zu Berlin* **5**: 82–93.

Behr, H.H. 1848b: Über die aussern Verhältnisse, welche auf die Entwickelung der Australier eingewirkt haben. *Monatsberichte über die Verhandlungen der Gesellschaft für Erdkunde zu Berlin* **5**: 145–149.

Behr, H.H. 1870: Synopsis noctuidarum hucusque in California repertarum. *Transactions of the American Entomological Society* **3**: 23–28.

Behr, H.H. 1881a: "An Adventure in the Philippine Islands. I". *Appletons' Journal: A Magazine of General Literature*: 339–347.

Behr, H.H. 1881b "An Adventure in the Philippine Islands. II". *Appletons' Journal: A Magazine of General Literature,* November: 385–395.

Behr, H.H. 1891: Botanical reminiscences. *Zoe* **2**: 2–6.

Behr, H.H. 1904: *The Hoot of the Owl* Robertson, San Francisco.

Garstenauer, W. 2013: South Australia als Ort von Wissenstradierung und Selbstbefragung im Zeichen des Komischen bei Hans Hermann Behr. *In* F.-J. Deiters, A. Fliethmann, B. Lang, A. Lewis and C. Weller (eds) *Limbus. Australisches Jahrbuch für germanistische Literatur- und Kulturwissenschaft/Australian Yearbook of German Literary and Cultural Studies.* Rombach, Freiburg i.Br **6**: Topos Australien, pp. 123–140.

Garstenauer, W. 2015: Politische Erinnerung als Unterhaltung: Die 1848er-Revolution bei Hans Hermann Behr. *In* A. Millner (ed.) *Empörung! Besichtigung einer Kulturtechnik* WUV, Vienna: pp. 55–74.

Germar, E.F. 1848: Beiträge zur Insektenfauna von Adelaide. *Linnaea Entomologica* **3**: 153–247.

Greer, R.A. 1969: The founding of the Queen's Hospital. *The Hawaiian Journal of History* **3**: 110–145 (Footnote 76, pp. 137–141).

Guztkow, F., Chismore, G. & Eastwood, A. 1905: *Doctor Hans Herman Behr: born August 18, 1818—died March 6, 1904.* California Academy of Sciences, San Francisco.

Jones, P. 2011: Colonial Wissenschaft: German naturalists and museums in nineteenth-century South Australia. *In* P. Monteath (ed.) *Germans: Travellers, Settlers and Their Descendants in South Australia.* Wakefield Press, Kent Town: pp. 204–236.

Kambang, A. [pseudonym for H.H. Behr] 1864: *Auf fremder Erde. Eine Roman. Mit einem Vorwort von Friedrich Gerstäcker.* [3 Vols] Costenoble, Jena.

Klug, J.C.F. 1850: Über die Lepidopteren-Gattung *Synomen. Abhandlungen der Königlichen Akademie der Wissenschaften zu Berlin* Aus dem Jahre 1848: 245–257.

Kraehenbuehl, D.N. 1981: Dr H.H. Behr's two visists to South Australia in 1844–45 and 1848–49. *Journal of the Adelaide Botanic Gardens* **3**: 101–123.

Legge, R.T. 1953: Hans Herman Behr: German Doctor, California Professor and Academician, and "Bohemian". *California Historical Society Quarterly* **32**: 243–262.

Leviton, A.E. & Aldrich, M.L. 1997: *Theodore Henry Hittell's The California Academy of Sciences 1853–1906.* California Academy of Sciences, San Francisco: p. 471 et seq.

Meier, U.H. 2005a: *Hawaii's Pioneer Botanist: Dr. William Hillebrand, His Life & Letters.* Bishop Museum, Honolulu: p. 8.

Meier, U.H. 2005b: *Hawaii's Pioneer Botanist: Dr. William Hillebrand, his Life & Letters.* Bishop Museum, Honolulu: p. 11.

Moran, B. 2013: *Mystery in the Stacks, Part II,* https://www.calacademy.org/blogs/from-the-stacks/mystery-in-the-stacks-part-ii (accessed 25 January 2016).

Mueller, F. 1855: Art. IV. Definitions of rare or hitherto undescribed Australian Plants, chiefly collected within the Boundaries of the Colony of Victoria, and examined by Dr. Ferd. Mueller. (Continued.). *Transactions of the Philosophical Society of Victoria* **1**: 34–50.

Santos, R.L. 1997: *The Eucalyptus of California: Seeds of Good or Seeds of Evil?* Alley Cass, Denair California: Section One.

Schlechtendal, D.F.L. 1847: Bestimmung und Beschreibung der von Dr. Behr in Südaustralien gesammelten Pflanzen. *Linnaea* **20**: 559–672.

Schlechtendal, D.F.L. 1848: Nachtrag zu den Südaustralischen Pflanzen des Hrn. Dr. Behr. *Linnaea* **21**: 444–452.
Swinhoe, C. 1892: *Catalogue of eastern and Australian Lepidoptera Heterocera in the collection of the Oxford University Museum.* Clarendon Press, Oxford: Part 1, Plate 7, Figure 10.

(Accepted 3 May 2016)

COSMOLOGY = TOPOLOGY/GEOMETRY: MATHEMATICAL EVIDENCE FOR THE HOLOGRAPHIC PRINCIPLE

by Adel N. Alahmadi and David G. Glynn

(with six text figures)

Alahmadi, A.N. & Glynn, D.G. 2016 (31:viii) Cosmology = topology/geometry: mathematical evidence for the Holographic Principle. *Papers and Proceedings of the Royal Society of Tasmania* 150(1): 31–38. ISSN 0080-4703. King Abdulaziz University, Jeddah, Saudi Arabia (ANA, DGG); CSEM, Flinders University, Adelaide, SA 5001, Australia (DGG*). *Author for correspondence. Email: david.glynn@flinders.edu.au

In August 2015 NORDITA (Nordic Institute for Theoretical Physics) hosted a conference where Hawking strongly supported the conjectured relationship between string theory and quantum fields that was initiated with the holographic principle some 20 years ago by 't Hooft, Maldacena, Susskind and Witten. We bring together results of several papers showing how mathematics can come to the party: the fundamentals of flat (even higher-dimensional) space can be derived very simply from topological properties on a surface. Specifically, Desargues, Pappus or other configurations do not have to be assumed *a priori* or as self-evident (a fundamental weakness of Hilbert's work in 1899) to develop the foundations of geometry. Are black holes places where non-commutative (quantum) behaviour reigns while Euclidean (flat) space is where commutativity holds sway? So, we cannot hope to look inside a black hole unless we know how "deformable" topology is related to "flat" geometry.

Key Words: cosmology, Desargues theorem, geometrical configuration, graph, history of mathematics, holographic principle, Pappus theorem, projective geometry, quantum mechanics, topological surface.

INTRODUCTION

Cosmology is about understanding the universe (Hawking 1988, Baker 2014). Many questions arise (Feynman 1992): what is space-time, how are particles related by forces? Start with the problem of space. Maybe it is Euclidean: flat or linear? It certainly looks superficially like that. The most recent advances point to a solution boiling down to holographic duality that must exist due to certain quantum constraints (Susskind 1995, 't Hooft 2000, 2009, Overby 2013, Cowen 2013). "Holographic" just means the conversion of a higher dimension to a lower one, or vice-versa, while "duality" has properties changing to analogous ones in the other. Thus the AdS/CFT or Maldacena duality (Maldacena 1998, 2013, Witten 1998) has been very useful in high-energy physics (Hamma & Markopoulou 2011). The IT from Qubit project based at Stanford University (IT from Qubit 2015), a collaboration funded by the Simons foundation (the Chern-Simons gauge theory is well-known) put forward a concise list of problems, in some sense related to the holographic principle with the "bulk", that is, what we perceive to be space, being (intuitively) surrounded by the lower-dimensional "boundary". Of course, geometers have had a similar idea for centuries: ordinary (affine) space has "points at infinity" which form a hyperplane, and together they form a far more symmetric structure, projective space. But the physicists are going one step further: they say that properties of the boundary are much more closely linked with the properties of the bulk.

The classical duality of projective geometry goes to the projective dual by a change of language: points change to hyperplanes and so on. There are many other transformations called "dualities". For example, "matroid theory" converts edges of graphs (vertices are connected by edges) to points in space (over any given commutative field of coordinates). Here we describe a fundamental duality, found in recent papers by the authors, relating topology and projective geometry: it may have applications in cosmology because the foundations of geometry form the prerequisite for cosmology.

Geometrical development in a nutshell is as follows: after Euclid in about 300 BCE, contributions by Pappus (320 CE), see the translation by Ver Eecke (1933), and Desargues, an associate of Descartes (Desargues 1639, Bosse 1648, Field & Gray 1987), non-Euclidean geometry arrived in the nineteenth century CE. In the beginning this involved Gauss (unpublished work) and the mathematicians Bolyai and Lobachevsky.

Thus one of the main and fundamental areas of geometry, projective geometry, was developed, first by the French (Carnot 1803) and then by the English, Germans and Italians in the nineteenth century. The Frenchman Poncelet wrote notes on geometry in a Russian military prison from 1812–1814, followed by the Germans Möbius (1828), Grassmann the elder (1844) and Karl Von Staudt (1847), the nobleman from Rothenburg ob der Tauber (see Plaumann & Strambach (1981) for Staudt's innovative point of view). Following this tradition came Felix Klein and his "Erlangen Program" (Klein 2004). This program says that groups of symmetries are equivalent to the various kinds of geometry. It had all kinds of developments, including the use of group representations in physics to represent particles. In Klein (1926–27) there is also a valuable history. Most groups involved with physics are "Lie" or continuous groups; Sophus Lie was a Norwegian associate of Klein. In the twentieth century the geometry was generalised, with technical details such as linear dependence properties being better explained by Whitney's theory of matroids. Late in the nineteenth century, prompted by the foundational work of the Englishman Cayley and the German Riemann (1854), Klein, Poincaré, Minkowski, then Einstein incorporated higher-dimensionality to explain space-time properties like relativity and gravity. The speed of light is basically constant, and space is deformed by mass, a property that can be explained by assuming the equivalence of spatial

frames of reference (Feynman 1992). Some works devoted to the foundation of geometry are: Russell (1897), Hilbert (1902) and Robinson (1940).

Theories such as M-theory and the standard model of particle physics suppose many dimensions of geometrical space: particles and forces may be strings vibrating according to some representations of groups; see Strogatz (2003), Connes (2004) and Gefter (2014a, 2014b). Dark matter seems to interact only very weakly with our visible world, giving unsolved problems, but is thought by some theorists to affect our space, and gravity, via other dimensions. However, most physicists rely at the basic level on properties of straight lines, flat planes, real number systems, all deriving from Euclidean roots and traditions. Klein (1926–27) knew that non-Euclidean geometry is just usual flat geometry with a change of metric given by a quadratic form.

Glynn (2013) and Alahmadi & Glynn (unpublished) have shown that the basic properties of linear geometry are derived from low-dimensional topology. Specifically, on well-known topological surfaces (with very important holes), there are two-dimensional structures, maps, that are continuously deformable, preserving the properties of points and arcs joining them, and regions confined by these arcs: we can say that these should lead to the most basic linear geometry. Anyone can now use topology to construct the linear configurations that were shown to be fundamental. Furthermore, the topological counterparts are simpler and more general in many cases.

Thus it does look like, from the mathematical point of view, that space itself is like a hologram: a kind of higher-dimensional illusion formed by properties that are really only two-dimensional, no matter how many dimensions we appear to detect with our senses or advanced physical devices. Sometimes art precedes science: Picasso already had realised that art is made from illusions. Cubism and unusual works forced people to think about reality (Gombrich 1977). It is probably no coincidence that Cubism developed around the same time as Einstein's revolution in physics: the first decade of the 1900s.

In the past, physicists such as Feynman have had some doubts when it comes to extending linear geometry down to microscopic quantum (or Planck) scales:

> *The theory that space is continuous is wrong, because we get these infinities and other difficulties, and we are left with questions on what determines the size of all the particles. I rather suspect that the simple ideas of geometry, extended down into infinitely small space, are wrong. Here, of course, I am only making a hole, and not telling you what to substitute. If I did, I should finish this lecture with a new law.* (Feynman 1992, pp. 166–167)

But Dirac, one of the founders of quantum mechanics, relied on geometric foundations, in particular projective geometry, to obtain his theories (Farmelo 2005, Galison 2000). This led to his joint Nobel prize with Schrödinger in 1933. In the upper right of figure 1 we see Dirac has drawn the 9 point 9 line Pappus configuration, "fundamental" for geometers. We shall see how to obtain this theorem in projective geometry using the duality with topology (in several ways). Pappus is known as the main property of space related to the multiplicative commutativity ($xy = yx$) of the field of coordinates.

Heisenberg, when it came to the important non-commutativity, $A \times B \neq B \times A$ of observables in quantum physics, as compared with the more intuitive commutativity $A \times B = B \times A$ of Newtonian physics, was at first surprised (Galison 2000). But we shall see that non-commutativity (of the coordinate field) comes naturally from planarity of graphs. Might it be that it is just areas on a fundamental (or "cosmic") surface that have no holes that are quantum? We expect our new duality to support the physics.

IDEAS FROM MATHEMATICS

Here we recall some basic topology, graph theory, projective geometry and matroid theory, giving a quick history and some references.

The topology of orientable surfaces

This is quite a modern area that has infiltrated diverse areas from deep algebraic geometry with the study of algebraic curves, to the combinatorics of graphs. The origins of topology were with Euler (1741) and Listing (1847), see also

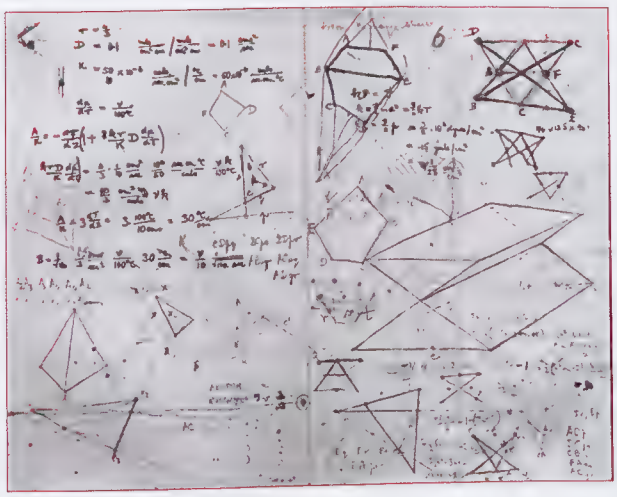

FIG. 1 — Paul Dirac, sketches.

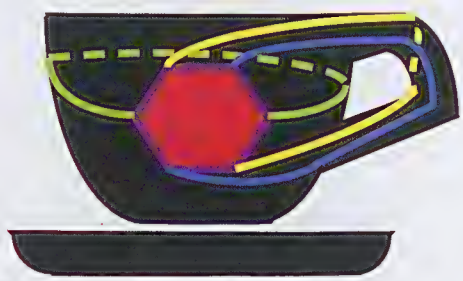

FIG. 2 — Geometry on a coffee cup: the toroidal graph $K_{3,3}$ with six vertices, nine edges and three hexagonal faces. The vertices are those on the central red hexagon, which has six purple edges. There are three further edges that use the handle to avoid each other. The two other faces each have three purple edges which alternate with the green, the blue and the yellow.

Tait (1883), and Poincaré (1895). We need some theory of graphs on surfaces, and more details, also with connections to physics, which can be found in Mohar & Thomassen (2001), Franzosi & Guadagnini (1996), Nash & Sen (1983) and Stewart (1987).

We only need to know about closed oriented or orientable surfaces. (Compact Riemann surfaces have additional (complex) structure but we don't use these.) The surface of a ball, a doughnut, a coffee cup (fig. 2), are all archetypal examples of closed orientable surfaces. We contemplate the surface of such an object: it has no clear boundary curves – it is "closed" – and locally within a limited region, it could as well be flat. But globally, or looking from an external viewpoint, the ball and the doughnut are different, and the important difference is measured by the number of holes it has: the "genus". Then the doughnut and the coffee cup are topologically the same. For a sphere the genus is zero, whereas for a doughnut, mathematicians call it a "torus", the genus is one. Here, we don't talk about spheres or doughnuts, but we refer to them as surfaces of genus 0 or 1. The orientable nature of the surface comes in when we draw a small circle around any point on the surface. Then the circle can be given a natural cyclic order (clockwise or anticlockwise). If the surface is "connected", which we always assume, in a continuous move, without jumping at any stage from the surface, one can go to any other point, and the cyclic ordering on the surface is consistent: it cannot change from clockwise to anticlockwise in a continuous manner. Given an "orientable" surface, choosing one oriented direction, e.g., clockwise, at each of its points, makes it "oriented". What this also means in practice, is that the surface is "two-sided". Think about the sphere for example. There is an inside surface and an outside surface. A small clockwise circle on the outside induces a small anticlockwise circle on the inside, and vice-versa. So the outside and the inside are separated topologically. There are also closed non-orientable surfaces: a change of the German umlaut to an "s" changes "kleinsche Fläche" (Klein's surface) into "kleinsche Flasche" (Klein's bottle); and there are non-orientable surfaces with boundary, such as the Möbius strip ("Band" in German), actually first published by Listing (1847), but these are not of major importance here. Linear geometry appears to be connected with certain properties of closed orientable surfaces and we can't yet see a connection with the other types of surfaces.

Graphs and maps on orientable surfaces

A graph (Tutte 1959) is a finite collection of points (called vertices), and a finite collection of "edges", or for physicists perhaps "strings" between the points. Usually, these edges are defined by unordered pairs or subsets {X,Y} of two distinct vertices (if the graph is "simple"). The direction of the edges, from X to Y or from Y to X does not matter. (Non-simple) graphs with more than one edge between two vertices are said to have "multiple" edges.

Now a general graph may be embedded on a surface: the vertices become points on the surface, and the edges are arcs that do not meet on the surface except at their end-points. Any collection of arcs going around in a circuit and finishing at the same place will enclose a certain area on the surface, and if the surface is orientable, the surface will be cut into several pieces. In particular, if the circuit is minimal and contains none of the holes in the surface, then the interior of the circuit is a region or face of a certain map: we say that the face is "contractible" continuously to a point. The interiors of all the faces of the map will cover all the points of the surface, all except for the vertices of the graph and its edges. Each edge will lie on the boundary of two faces (except for some degenerate situations).

The number of holes in an orientable surface is called its genus g, which is a "homotopy" invariant: that is, two orientable surfaces of the same genus are deformable to each other. They have the same combinatorial properties, and it is these properties that we need.

It is a fundamental fact that if we have a graph having v vertices, e edges, and f faces on an orientable surface of genus g, then $v-e+f = 2-2g = \chi$, the Euler–Poincaré characteristic, which relates v, e, f, g by a linear equation.

For example, the graph K_4, the *complete* graph with four vertices and having all possible six edges, is clearly embeddable on the surface of a sphere in Euclidean space: it is a tetrahedron, and then there are four faces, so that $v = f = 4$, and $e = 6$, satisfies $v-e+f = 2$. So it checks out that $g = 0$ on a sphere.

Projective geometry

For the modern foundations of projective geometry one looks to Hilbert (1902). Soon after this appeared Veblen & Young (1910, 1917) produced simple axioms for projective geometry. Thus a projective space S = (P, L, I) is assumed to be a set of points P, with a set L of subsets of P called "lines". If a point p is in (or "on") a line r we say that the point and line are "incident": this defines the incidence relation pIr. Points on the same line are said to be "collinear". Then there are some axioms (Dembowski 1968, pp. 45–46):

1. Every line has at least three points (Fano axiom).
2. Any pair of distinct points p, q are contained in a unique line denoted by pq.
3. For any "triangle" a, b, c of distinct non-collinear points, any pair of lines not through a that intersect the lines ab and ac non-trivially will have a common point (Veblen axiom).

A "subspace" of S is a subset of points, closed under the operation of joining points together to form lines, i.e., it is a set T of points such that $p, q \in T$ implies $pq \subseteq T$. The set of all subspaces of S is defined to be the "projective geometry" based on S. The subspaces, increasing in size, are the empty set Ø, the points (singleton sets), the lines, the planes (generated by triangles), and so on up to the hyperplanes, and the whole space. The "rank" of a subspace is the size of a minimal set of points that it has, generating the whole subspace, and then the "dimension" is the rank minus one. For any pair of subspaces U, V there is an important dimension formula, (often called Grassmann's formula): $\dim U + \dim V = \dim UV + \dim U \cap V$. Here UV is the smallest subspace containing U and V; and $U \cap V$ is always a subspace.

Projective geometry of dimension more than one can be divided into three basic camps:

1. Projective (pappian) geometry over a field F that is commutative, e.g. the real numbers R or the complex numbers C;
2. Projective (desarguesian) geometry over a field F that is non-commutative (called "division ring" or "skewfield", e.g., Hamilton's quaternions H);
3. General projective planes (of dimension two), not usually having any base field, but instead more general coordinates such as over a quasifield, semifield or nearfield (Dembowski 1968).

For us, the interest lies in projective geometry (1) and (2). Even though (3) has great theoretical interest we ignore this possibility from now on, since it is well known that a projective geometry of dimension at least three must be one of the first two types. A proof uses Desargues and Pappus ctheorems (see Veblen & Young 1910, 1917). Thus we assume that the most general projective geometries are over a field where we don't know if it is commutative or not: Desargues ctheorem (see later) is an example of a property of space that holds in the most general projective geometries, but Pappus theorem would hold only for "commutative" projective geometries.

An affine space, or geometry, can be easily embedded into a projective geometry by adjoining a unique hyperplane at infinity. This is just another set of points that are defined by the parallel classes of lines. Conversely, any affine geometry (such as the Euclidean one), can be constructed from the projective geometry by deleting the hyperplane at infinity. Usually it is better for foundational work to use the projective geometry, since the axioms are much simpler. In general, in terms of collineation groups (Klein's Erlangen Program point of view), projective geometry corresponds to the transformations by non-singular matrices, while affine geometry corresponds to more complicated affine transformations.

We let PG(n,F) be the projective geometry of dimension n over a field F. It can be shown to be unique, subject to the proviso that if the field is non-commutative there could be two projective geometries related by anti-isomorphism, switching left and right, but it really is not important.

The easiest way to learn about it is to first understand the mathematical theory of fields F, and then go through the axioms of a vector space $V=F^{n+1}$ of dimension $n+1$ over F. If F is non-commutative one has to choose either a left or right vector space. Then the projective geometry over F of dimension n is just the set of all vector subspaces of V. A vector subspace of rank $i+1$ corresponds to a projective subspace of dimension i. The language of vectors also changes to geometrical language. The vector subspace {0} is just the empty set of points;

- a vector subspace of all multiples of a vector is just a point;
- a vector subspace generated by two independent vectors is just a line;
- a plane is generated by three independent vectors;
- a hyperplane is a vector subspace of generated by n independent vectors;
- and $n+1$ vectors generate the whole space which is the same as the projective geometry PG(n,F).

Of course, one may dispense with algebra and choose to define projective geometry from a few lines of simple axioms that we gave above, but in practice, one needs the backup of algebraic coordinates (mostly "homogeneous" or "projective" coordinates) to solve many problems. A big part of it, though, is psychological: people are reassured when they use coordinates or vector spaces to construct geometry. It is like having nuts and bolts instead of abstract notions and axioms. However, nuts and bolts can also weigh one down: often things are more efficient if unnecessary items are discarded.

Matroid theory

This is a more recent theory developed by Hassler Whitney (1935), followed by W.T. Tutte starting in the late 1940s; see Tutte (1959). It has been shown to be critical for a proper understanding of abstract ideas in geometry involving linear dependence, i.e., the concepts of basis, spanning set, circuit etc. Although we do not need the theory directly here, there are parallels with the idea of duality: e.g., each graph (not necessarily topological), corresponds to a circuit matroid, which is a configuration in geometrical space. A planar graph has a dual (switching vertices and faces) which gives the dual matroid, which, algebraically, comes from a kind of orthogonal space.

FUNDAMENTAL THEOREMS

Let S be an orientable (two-sided) surface of genus g. This could well be associated as in the holographic principle with a "cosmic" surface that is the boundary of the "bulk": the CFT (lower-dimensional) side of the Maldacena duality. Let G be a graph with possible multiple edges that is embedded on S. It has a map $M(G)$ with v vertices, e edges, and f faces, so that the Euler characteristic equation is $v-e+f = 2-2g$. From the orientability one can put a clockwise orientation of the edges around each vertex of G, which induces an anticlockwise orientation around the inside of the face, and clockwise on the outside.

We give the two main theorems without proofs, which use topological reductions, and special kinds of determinants, some of which are valid also for non-commutative fields. The two theorems have different methods to produce "ctheorems" of slightly different types from the graph G. Abstractly, a ctheorem is a set D of subsets of a finite set C, such that when the elements of C are considered to be points in a given projective space, and when each subset in D is now a (linearly) dependent set of the embedding, then all but one of the dependencies imply the remaining one. Recall that a "dependent" set has the (matroid) property that the subspace generated by some proper subset encloses the entire set. Thus ctheorems are special kinds of geometrical configuration, which describe the properties of linear space. Alahmadi & Glynn (unpublished) have shown that the two main theorems produce ctheorems from the same (embedded) graph G which are projectively dual when looked at in certain way: the two main theorems here are giving two sides of the same coin. However, direct methods to prove one theorem from the other, and other connections, could be explored further.

Most importantly, the ctheorems that either of the Theorems 1 and 2 produce are valid for the projective geometries of both types (1) and (2) over the most general division rings F if the surface S has genus $g=0$. That is, G is a planar graph and the surface has no holes. The ctheorems extracted from either of the Theorems 1 and 2 using surfaces with at least one hole are valid for all projective geometry of type (1) over commutative fields F. This provides an explanation (for perhaps the first time) for the major dichotomy in projective geometry between commutative and non-commutative fields.

Theorem 1 (Glynn 2013)

The graph G gives rise to a geometric property of general projective space. This is a configurational theorem (we call it more briefly a "ctheorem") having $v+f$ points and e subsets (dependencies) of v points, each in a hyperplane of PG($v-1$,F). For any embedding of the ctheorem, if $e-1$ of the hyperplanes are known then in general the final hyperplane also exists.

Construction of the ctheorem:

- The vertices and faces become the points of the configuration.
- Each edge becomes a hyperplane containing the v–2 vertices not on the edge, and also the two faces of which the edge is a boundary.

Note: There is a (topological or matroid) dual ctheorem which switches the roles of vertices and faces, and so has $v+f$ points and e hyperplanes in PG(f–1,F). Using projective duality there are also ctheorems with e points and $v+f$ hyperplanes in PG(v–1,F) or PG(f–1,F).

Theorem 2 (Alahmadi & Glynn unpublished)

The graph G gives another ctheorem in PG(n,F), where Max(G) ≤ n+1 ≤ v, (Max(G) is the size of the largest face of G), having $v+e$ points and $e+f$ dependencies.

Construction of the ctheorem:

- The vertices and edges become the points of the configuration.
- Each edge gives a dependent line of three points, the two end vertices of the edge and the edge itself. (It follows that if there are m multiple edges between two vertices all the corresponding m+2 points in the ctheorem are collinear.)
- Each face of G gives a dependent set of edges, those edges on the boundary of the face. See figure 3.

Notes:

- As in Theorem 1, Theorem 2 could use the (topological) dual graph of G on the surface (changing around vertices and faces, or v and f) giving another ctheorem. However, in this case the ctheorem is not the matroid dual.
- The bound for the dimension n of the space in Theorem 2 is to prevent degeneracy.
- The Theorem 2 construction is related to (but not the same as) the classical way to get a configuration from a graph in matroid theory: for the *circuit matroid* of a graph one maps edges to points in projective space PG(v–1,F) (F commutative), and circuits in the graph to minimal dependencies. However, Theorem 2 is clearly quite different, since the circuit matroid of a graph is almost never a ctheorem, and it is not defined for non-commutative fields.

EXAMPLES

Hilbert (1902) showed that the properties of projective geometries (1) can be built up starting with Pappus ctheorem (fig. 6), and for projective geometries (2) with Desargues ctheorem (fig. 4). Both Pappus and Desargues are planar (two-dimensional) ctheorems of types n_3, where n = 9 and 10 respectively, with n points, n lines, three points on each line, three lines through every point.

Hessenberg (1905) showed how to prove Desargues synthetically (using no algebra) given that Pappus holds: this is equivalent to the fact that the commutative fields are more specialised than non-commutative ones. For our duality it is the condition that a graph be planar.

Desargues ctheorem (Desargues 1639, Bosse 1648)

The complete graph on v = 4 vertices, K_4, is planar, having e = 6 edges and f = 4 triangular faces in its embedding. The orientable surface has genus zero and so Theorem 2 implies a configurational theorem having $v + e$ = 10 points, e = 6 line dependencies and an additional f = 4 face dependencies, which in this case are lines. Notice also that it is a theorem in both 2- and 3- dimensional space, since 3 is the minimum face size of K_4, and there are 4 vertices in the graph. Since the surface has genus zero, the theorem from K_4 is valid for all projective spaces over fields or skewfields. It is Desargues ctheorem.

In fig. 4 one can check that each triangular face of K_4 corresponds to a unique dotted line. Thus in total there are 10 lines, six from the edges of K_4, and four dotted lines from the faces. Notice that the outside face must be included.

It is to be noted that if one used Theorem 1 instead of Theorem 2, the bundle theorem of 3- space would be obtained. Hence there are two ctheorems, in some way related by projective duality, coming from the same planar graph.

Pappus (hexagon) ctheorem (Pappus 320 CE)

The graph needed by Theorem 2 is a topological dual of the nonplanar graph $K_{3,3}$ (the complete bipartite cubic graph having six vertices), embedded on the torus, of genus g=1,

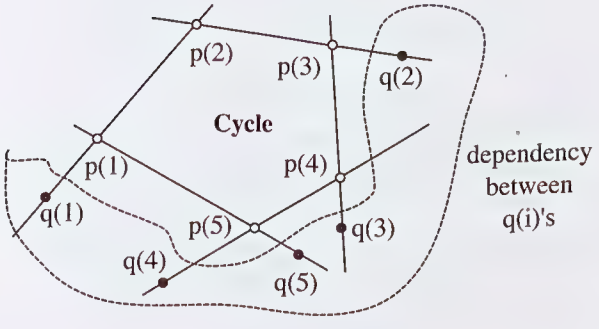

FIG. 3 — Cycle dependency (p's are on the boundary surface S and q's are bulk points).

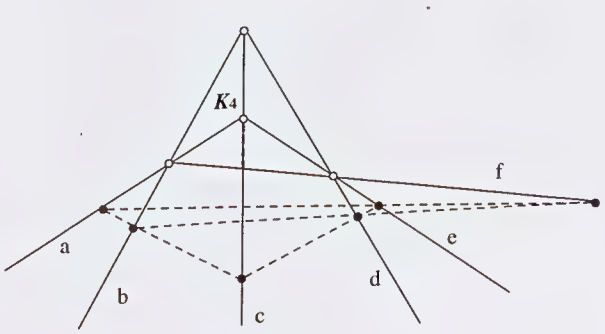

FIG. 4 — Complete planar graph K_4, using Theorem 2, implies Desargues ctheorem.

drawn in figure 2. That graph had three hexagonal faces, six vertices, and nine edges, so the dual needed (by flipping vertices and faces) for Pappus has three vertices, nine edges and six faces. First we have to draw it in another way.

There are several ways of thinking about a torus. The classical way is to consider any parallelogram in the Euclidean plane, and let it generate a tessellation covering all the points of the plane. Then it is clear that modulo this parallelogram, the opposite sides are identified with each other in the obvious way. It turns out that then the points inside and on the boundary (with the given identification of opposite sides) is the torus.

However, we shall use a slightly different, but actually equivalent method to represent the torus. Consider a regular hexagon in the same Euclidean plane. It also corresponds to a tessellation (or tiling) of all the points. Similarly, we identify the opposite sides of the hexagon, and it turns out that the points on the hexagon again form a torus. The three alternating points on the boundary of the hexagon correspond to the same point on the torus. Then we can split the hexagon into six triangles all touching at the central point as in figure 5.

This gives the graph $3C_3$ (the 3-cycle with each edge repeated thrice) with three vertices, *X*, *Y* and *Z*, and nine edges *a*, *b*, *c*, *d*, *e*, *f*, *g*, *h*, *i*. Thus we are basically tiling the hexagons over the Euclidean plane, and this map on the torus corresponds to a tesselation into triangles that are inside the tesselation of larger hexagons. Bees already know of the most efficient way to cover the plane! (Hales (2001) proved this.)

Theorem 2 shows that the lines of Pappus (displayed in fig. 6) are of two types: coming from triples of edges between the same two vertices, e.g., XY gives the edges *a*, *b*, *c*; and *b*, *d*, *g* comes from a face.

Pappus lies in two-dimensional space: the graph has three vertices, so an upper bound for the dimension is two; and the largest face of the map induced by $3C_3$ is also three; so a lower bound for the dimension is two. Thus Pappus is a ctheorem for 2-d space, the projective plane. The plane must also be coordinatised by a commutative field, since the genus of the torus is one, which is greater than zero (one hole is there in the surface).

Theorem 1 can also be used to construct a ctheorem from the same graph $3C_3$, and it turns out that it is the same Pappus theorem! Indeed, we have already noted that, although it is not immediately obvious, the ctheorems arising from Theorems 1 and 2 are projective duals of one another when viewed in the right way. Pappus is a projectively self-dual configuration (as one sees by switching points and lines), so the two Theorems give the same thing. For Theorem 1, one can take the three points *a*, *f*, *g* to be the vertices of the graph, and the faces to be the remaining points of Pappus: *b*, *c*, *d*, *e*, *h*, *i*. Then the edges are the nine lines. For example, the line *a*, *b*, *c* corresponds to the edge between faces *b* and *c* having the two vertices *f* and *g* as end points.

Further comments

There are precisely two 8_4 ctheorems of eight points and eight planes in 3-d space over a commutative field, both projectively self-dual; see Glynn (2010). Both have been described figuratively as two tetrahedra that simultaneously inscribe and circumscribe each other. There are five ways of doing this, each way corresponding to a conjugacy class of the symmetric group S_4, but only two ways give ctheorems. The first 8_4 (Möbius 1828) may be obtained, using either of the Theorems 1 and 2, from the graph $2C_4$ (the 4-cycle with each edge repeated twice), embedded on the torus with four faces). The second 8_4 may be obtained similarly from the graph K_4 plus two disjoint edges also embedded on the torus with four faces; see Glynn (2013) and Alahmadi & Glynn (unpublished).

Reidemeister configuration in the plane (Reidemeister 1929) is known to be a ctheorem which is algebraically equivalent to the associativity of the additive and multiplicative rings of coordinates for projective planes (Dembowski 1968). Using Theorem 2 its projective dual corresponds to the planar octahedral graph of six vertices, 12 edges, and eight triangular faces with opposite vertices identified or "pinched" together. The process of "pinching" vertices (Archdeacon, Bonnington & Siran 2014) is a way of obtaining a lower dimensional ctheorem from a higher dimensional one. It corresponds to a projection of the

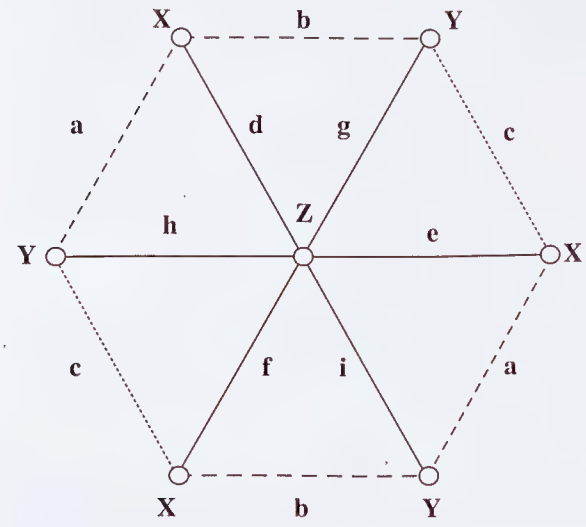

FIG. 5 — Graph $3C_3$ on the torus, dual to the coffee cup drawing in figure 2.

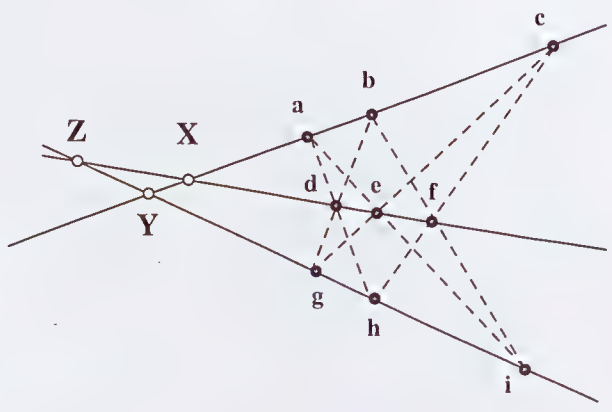

FIG. 6 —Toroidal graph $3C_3$ (fig. 5), using Theorem 2, implies Pappus ctheorem.

projective space, and each pinching of a pair of vertices makes the dimension one lower. In this case, five dimensions are projected into two dimensions; see Alahmadi & Glynn (unpublished).

Consider the planar graph on four vertices: a square with four edges and a diagonal edge. So there are five edges in total and three faces. Then using Theorem 2 one obtains a ctheorem about 3-d space, related to the fact that two lines that intersect are found in a plane. Conversely, in projective geometry coplanar lines must intersect non-trivially.

In axiom systems for projective geometry it is normally assumed a priori that a "line" is a set of points, and then every three of these points are linearly dependent. However, the topology/geometry duality could actually explain this. For example, consider figure 5, which is a hexagon with a central point on the torus. Delete the central point and the six edges through it. There remains a hexagon covering all the torus, folded on itself three times, inducing a graph with two vertices *X* and *Y*, edges *a*, *b*, *c* and a single face *abc*. Using Theorem 2 the resulting ctheorem is: if *X*, *Y*, *a*, *b*, *c* are five points, and *XYa*, *XYb*, *XYc* are three dependent (that is, collinear) sets, then *abc* are also collinear.

Interesting papers and a recent book about areas of quantum, strings, and non-commutativity are Twamley (1997), Agagnic (2016), Jones (1987) and David (2015).

ACKNOWLEDGEMENTS

The authors acknowledge support from King Abdulaziz University, Saudi Arabia.

REFERENCES

Aganagic, M. 2016: String theory and math: why this marriage may last. Mathematics and dualities of quantum physics. *Bulletin of the American Mathematical Society* **53**: 93–115.

Alahmadi, A.N. & Glynn, D.G. unpublished: The duality of topology and geometry: why is it So? In submission.

Archdeacon, D., Bonnington, C.P. & Siran, J. 2014: Regular pinched maps. *Australasian Journal of Combinatorics* **58**: 16–26.

Baker, J. 2014: Cosmology: first light. *Nature* **509**: 276–278.

Bosse, A. 1648 *Manière Universelle de M. des Argues pour Pratiquer la Perspective par Petit-pied, Comme le Géomètral: Ensemble les Places et Proportions des Fortes; Foibles Touches, Teintes ou Couleurs.* Des-Hayes, Paris.

Carnot, L.M.N. 1803: *Geometrie de Position.* Paris.

Connes, I. 2004: Symmetries. *European Mathematical Society Newsletter* (December).

Cowen, R. 2013: Simulations back up theory that Universe is a hologram. *Nature News* 10th December.

David, F. 2015: *The Formalisms of Quantum Mechanics.* Lecture Notes in Physics **893**: Springer, Heidelberg.

Dembowski, P. 1968: *Finite Geometries.* Ergebnisse der Math. **44**: Springer, Berlin.

Desargues, G. 1639: *Brouillon Project d'une Atteinte aux Événemens des Rencontres d'une Cône avec un Plan.* (Self-published 50 copies.) English translation, Lloyd Kannenberg 1995: *A New Branch of Mathematics.* Open Court, Chicago.

Euler, L. 1741: Solutio problematis ad geometriam situs pertinentis. *Commentarii academiae scientiarum Petropolitanae* **8**: 128–140. (Presented to St. Petersburg Academy, 26 August 1735.)

Farmelo, G. 2005: Dirac's hidden geometry. *Nature* **437** (15 Sept): 323.

Feynman, R.P. 1992: *The Character of Physical Law.* Penguin, London: 173 pp.

Field, J.V. & Gray J.J. 1987: *The Geometrical Work of Girard Desargues.* Springer Verlag, New York.

Franzosi, R. & Guadagnini, E. 1996: Topology and classical geometry in (2+1) gravity. *Classical and Quantum Gravity* **13**: 433–460.

Galison, P. 2000: The suppressed drawing: Paul Dirac's hidden geometry. *Representations* **72**: 145–166. University of California Press.

Gefter, A. 2014a: M is for mystery, how our best theory of everything got its name. *New Scientist* (19 April). dx.doi.org/10.1155/2013/379074.

Gefter, A. 2014b: *Trespassing on Einstein's Lawn.* Bantam Press, New York.

Glynn, D.G. 2010: Theorems of points and planes in three-dimensional projective space. *Journal of the Australian Mathematical Society* **88**: 75–92.

Glynn, D.G. 2013: A rabbit hole between geometry and topology, *ISRN Geometry* **2013**: Article ID 379074, 9 pp.

Gombrich, E.H. 1977: *Art and Illusion A Study in the Psychology of Pictorial Representation.* Phaidon Press, Oxford.

Grassmann, H. 1844 *Die lineale Ausdehnungslehre.* Wiegand, Leipzig: Second edition. 1861.

Hales, T.C. 2001: The honeycomb conjecture. *Discrete and Computational Geometry* **25**: 1–22.

Hamma, A. & Markopoulou, F. 2011: Background independent condensed matter models for quantum gravity. *New Journal of Physics* **13**:095006.

Hawking, S.W. 1988: *A Brief History of Time.* Bantam Press, London: 198 pp.

Hessenberg, G. 1905: Beweis des desarguesschen Satzes aus dem pascalschen. *Mathematische Annalen* **61**: 161–172.

Hilbert, D. 1902: *The Foundations of Geometry.* Open Court, Chicago.

IT from Qubit 2015: *Simons Collaboration on Quantum Fields, Gravity, and Information*, web.stanford.edu/~phayden/simons-proposal.pdf. (accessed 19 November 2015).

Jones, J.D.S. 1987: Geometry goes non-commutative. *Nature* **329**: 201.

Klein, F. 1926–27: *Vorlesungen über die Entwicklung der Mathematik im 19. Jahrhundert*, Two Volumes, Berlin. Reprinted 1967: Chelsea, New York.

Klein, F. 2004: *Elementary Mathematics from an Advanced Standpoint: Geometry.* Dover, New York. Section on the 1872 Erlanger Programm.

Listing, J.B. 1847: *Vorstudien zur Topologie.* Göttingen Studien.

Maldacena, J. 1998: The large N limit of superconformal field theories and supergravity. *Advances in Theoretical Mathematical Physics* **2**: 231–252.

Maldacena, J. 2013: The illusion of gravity. *Scientific American* **293(5)**: 56–63 (July).

Möbius, A.F. 1828: Kann von zwei dreiseitigen Pyramiden einejede in Bezug auf die andere um- und eingeschrieben zugleich heissen? *Crelles Journal* **3**: 273–278. *In* Klein, F. (ed.) 1886: *Gesammelte Werke.* Leipzig, vol. 1, 439–446.

Mohar, B. & Thomassen, C. 2001: *Graphs on Surfaces.* Johns Hopkins University Press, Baltimore.

Nash, C. & Sen, S. 1983: *Topology and Geometry for Physicists.* Academic Press, London. Paperback Dover 2011.

Overby, D. 2013: A black hole mystery wrapped in a firewall paradox. *New York Times* (August 12).

Pappus 320 CE: *Collection*, Book VII. Royal Library, Alexandria, Egypt.

Plaumann, P. & Strambach K. 1981: *Geometry – Von Staudt's Point of View.* Reidel. Proceedings of the NATO Advanced Study Institute, Bad Windsheim, West Germany, 21 July–1 August 1980.

Poincaré, H. 1895: Analysis situs. *Journal de l'École Polytechnique* (2)**1**: 1–123.

Reidemeister, K. 1929: Topologische Fragen der Differentialgeometrie. V. Gewebe und Gruppen. *Mathematische Zeitschrift* **29**: 427–435.

Riemann, B. 1854: Über die Hypothesen, welche die Geometrie zugrunde liegen (About the hypotheses, which lie at the heart of geometry.) Habilitation Lecture, Göttingen, 10 June. Shared by Dedekind, R., 1868: *Abhandlungen der Königlichen Gesellschaft der Wissenschaften zu Göttingen* **13**: 133–152.

Robinson, G. de B. 1940: *The Foundations of Geometry.* University of Toronto Press, Toronto. Book review, 31 January 1942: *Nature* **149**: 125.

Russell, B.A.W. 1897: *An Essay on the Foundations of Geometry*, Cambridge University Press, Cambridge. Book review, 1897: *Nature* **56**: 417–418.

Stewart, I. 1987: Topology: The hyperbolic phoenix. *Nature* **328**: 16.

Strogatz, S. 2003: *Sync: The Emerging Science of Spontaneous Order.* Hyperion Press.

Susskind, L. 1995: The world as a hologram. *Journal of Mathematical Physics* **36**(11): 6377–6396.

Tait, P.G. 1883: Johann Benedict Listing. *Nature* **27**: 316–317 (1 Feb.).

't Hooft, G. 2000: The holographic principle, Opening lecture, SPIN-2000/06. *In* Zichichi, A. (ed.): *Basics and Highlights in Fundamental Physics.* The Subnuclear series, vol. 37, World Scientific, 2001, 72–100. hep-th/0003004.

't Hooft, G. 2009: Dimensional reduction in quantum gravity. *In* Ali, A., Ellis, J. & Randjbar-Daemi, S. (eds.): *Salamfestschrift: A Collection of Talks.* World Scientific Series in 20th Century Physics, vol. 4 (World Scientific, 1993), THU-93/26. arXiv:gr-qc/9310026v2, 20 March.

Tutte, W.T. 1959: Matroids and graphs. *Transactions of the American Mathematical Society* **90**: 527–552.

Twamley, J. 1997: Quantum mechanics: statistics given a spin. *Nature* **389**: 127–129.

Veblen, O. & Young, J.W. 1910, 1917: Projective Geometry, volumes I and II. Ginn & Co., Boston.

Ver Eecke, P. 1933: Pappus d'Alexandrie, La Collection Mathématique. Oeuvre traduite pour la première fois du grec en francais, avec une introduction et des notes. Desclée de Brouwer, Brugge/Paris.

Von Staudt, K.G.C. 1847: *Geometrie der Lage.* F. Korn, Nürnberg.

Whitney, H. 1935: On the abstract properties of linear dependence. *American Journal of Mathematics* **57**: 509–533.

Witten, E. 1998: Anti-de Sitter space and holography. *Advances in Theoretical and Mathematical Physics* **2**: 253–291.

(Accepted 5 July 2016)

GUSTAV THUREAU, FIRST TASMANIAN INSPECTOR OF MINES AND GOVERNMENT MINING GEOLOGIST

by G. L. McMullen

(with two text-figures, one plate and one table)

McMullen, G.L. 2016 (31:viii): Gustav Thureau, first Tasmanian Inspector of Mines and Government Mining Geologist. *Papers and Proceedings of the Royal Society of Tasmania* 150(1): 39–43. ISSN 0080-4703. Mary Aikenhead Ministries, Bondi Junction, NSW 2022, Australia. Email: gabrielle.mcmullen@maministries.com.au

From humble origins as a rebellious student in Clausthal, Germany, Gustav Thureau became the first Tasmanian Inspector of Mines and Government Mining Geologist. He brought to these offices his experience in Germany, South Australia, Victoria and, briefly, America as a miner, mine manager, lecturer, mining inspector, mining reporter and mining consultant. His 50-year career in mining is interspersed with a number of controversies.

Key Words: mining geology, Tasmania, Gustav Thureau.

INTRODUCTION

A range of peaks southeast of Queenstown in Tasmania is known as the Thureau Hills in acknowledgement of Tasmanian contributions made by Gustav Adolph Hugo Thureau (1831–1901) (pl. 1). Additionally, two Tasmanian fossils were named for him: a fossilised plant that he found at Mount Bischoff (*Taxites thureaui* Johnston), and the oldest known remains of a vertebrate in Tasmanian rocks which he discovered in the Mersey Coal Measures near Railton (Thureau's Microsaurian, subsequently identified as an eroded cephalopod, M.R. Banks pers. comm. 21 September 1994) (Johnston 1885, 1900–1901). What were Thureau's achievements that accorded him such recognition? These are presented in this paper and summarised in table 1.

PLATE 1 — Gustav Thureau by Whitelaw of Launceston, from the collection of Mineral Resources Tasmania and reproduced with kind permission.

GERMAN TRAINING

Thureau was born in 1831, one of the ten children of Wilhelm Gottlieb Thureau, a brewery administrator, and Dorothee Kreßner; he grew up in the mining town of Clausthal in Germany's Harz Mountains (McMullen 1996). From 1845 he attended the School of Mines attached to the renowned Clausthal Royal Academy of Mines, and trained as a mine foreman (Thureau 1889).

The political unrest of 1848 is generally associated with intellectuals but it was mining student Thureau, at the time the operator of an ore stamper, who led a demonstration at the Rosenhof Mine in August 1848. He was "sentenced to a ten-day prison term for attempting to incite a noisy riot" and left the School of Mines in disgrace — this episode was probably the first indication that Thureau would distinguish himself from those with whom he had grown up and who had had comparable educational opportunities (Oberbergamt [Mining Office] Clausthal-Zellerfeld 1848a).

Following his conviction and resulting unemployment Thureau left Clausthal. He appealed to the local authorities for support and had his passage to Australia funded (Oberbergamt Clausthal-Zellerfeld 1848b). Arriving in Adelaide in March 1849 (*The South Australian Register* 1849a, b), 17-year-old Thureau worked initially in the Burra Burra copper mines as an ore dresser (*The Bendigo Advertiser* 1878).

EMERGENCE OF THE MINING GEOLOGIST

In 1852, like many others, Thureau left for the Victorian goldfields (Victorian Certificate of Naturalisation 1859).

TABLE 1 — Stages of Gustav Thureau's career

Locations	Years	Career Stages
Germany	1845–1848	Royal School of Mines, Clausthal
South Australia	1849–1852	Copper mining at Burra Burra
Victoria	1852–1872	Miner, mining agent and mine manager at Forest Creek, Maryborough, Ararat, Malmsbury, Taradale, Ballarat, Daylesford, Warrandyte and St Arnaud
	1872–1877	Mining inspector, manager and reporter (*The Bendigo Advertiser*) in Bendigo
	1874–1877	Lecturer, Bendigo School of Mines
	1875	Fellow of the Geological Society
America	1877	Delegate to California and Nevada
Tasmania	1880	Consultant mining geologist
	1881	Consultancy for Government
	1882–1889	Inspector of Mines
	1887	Addition of title Government Mining Geologist
	1889–1891	Private practice
Victoria	1892–1899	Private practice, Melbourne
	1896	Member of the Geological Society of Australasia
	1897–1901	Councillor of the Geological Society of Australasia

He initially spent five years in Forest Creek as a miner and mining agent. He worked similarly in Maryborough for two years and then Ararat for a year before advancing to the position of mining manager at Malmsbury, Taradale, Ballarat, Daylesford, Warrandyte and St Arnaud (Victorian Certificate of Naturalisation 1859, Public Records Office of Victoria 1865) (see fig. 1). Thus, during his twenties and thirties, Thureau increasingly became an authority on mining and was, on occasions, designated mining engineer. He also gained a good command of written English and published detailed commentaries on mining – for example, in *The Colonial Mining Journal, Railway and Share Gazette* (1859, 1861a).

In 1860 Thureau and his colleague Adams discovered the "very promising" Humboldt Reef near Taradale, and the next year they also discovered iron ore in the vicinity (*The Colonial Mining Journal, Railway and Share Gazette* 1860, 1861b). However, within five years, Thureau was declared insolvent due to losses in mining ventures (Public Records Office of Victoria 1865, *Victorian Government Gazette* 1865, *The Argus* 1865). On later occasions Thureau was also in financial difficulties, suggesting a lack of business acumen.

In the early 1870s Thureau moved to Bendigo where he worked as inspector and then as manager of a number of mining companies (*The Bendigo Advertiser* 1878). He was appointed lecturer in practical engineering at the new Bendigo School of Mines in 1874 and its "first course in geology and mining" is attributed to him (Mackay 1914, Cusack 1973a). The following year Thureau's professional contributions were recognised in his election as a Fellow of the Geological Society of London (Thureau 1889). Significantly, his standing in Bendigo was such that he was selected in 1877 as the "qualified delegate" to go to the United States to report on mining methods there (Thureau 1879). He spent about three months in America and subsequently recommended certain innovations to

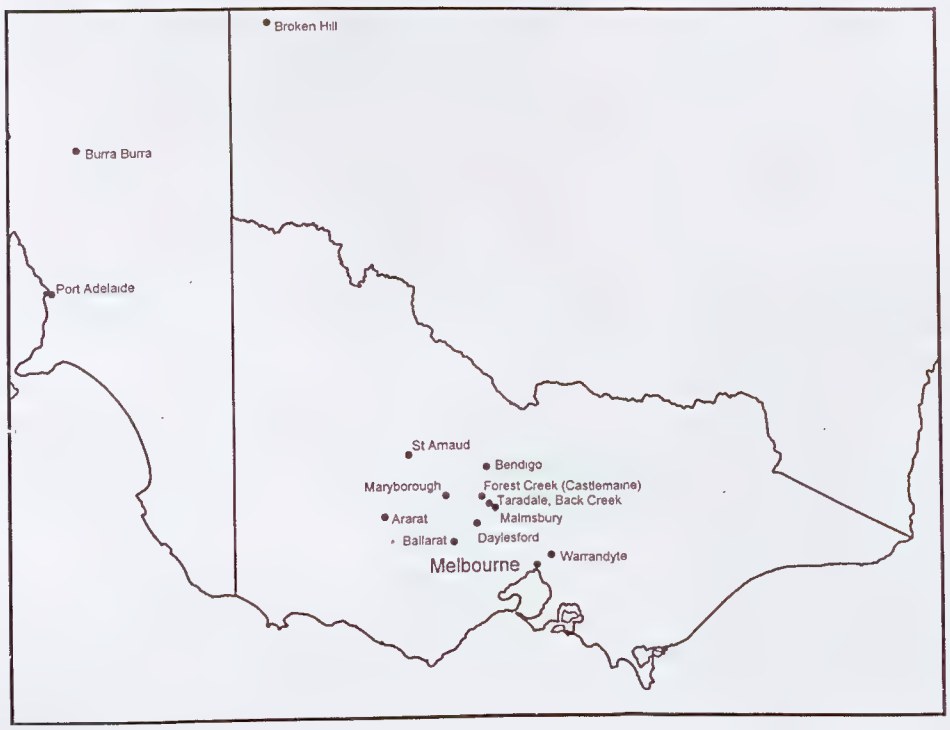

FIG. 1 — Locations on the Australian mainland where Thureau worked.

improve the efficiency of mining in the Bendigo region. He apparently resigned his lectureship at the School of Mines to accept the American assignment and, upon his return, the School did not have the funds to re-employ him and he was not able to find other work in Bendigo (*The Bendigo Advertiser* 1878, Cusack 1973b).

TASMANIAN INSPECTOR OF MINES

In search of new opportunities, in 1880, Thureau went to Tasmania, a decision which initiated a decade of his profound influence on geological surveying and mining in the island state (Certificate of Naturalisation Archives Office of Tasmania [AOT] 1885). Initially, he seems to have earned his livelihood there as a consultant and some of his reports of Tasmanian mines appeared in local newspapers (e.g., *The Launceston Examiner* 1881). Significantly, he soon had influential connections, including William Ritchie, a key figure in mining investment and a friend of Premier William Giblin.

In 1881 Ritchie suggested to the Premier that Thureau be employed by the Government to report on Tasmania's mineral resources. Thureau was enthusiastic about the consultancy and offered his services at an attractive rate, hoping to secure a permanent appointment (Ritchie 1881). The Premier wrote to Thureau requesting him to inspect and report "upon the various Gold Fields and Tin producing Districts of Tasmania" (Giblin 1881). He noted the difficulty of the assignment in winter but, at the same time, the importance of evaluating local mineral resources. That same year Thureau inspected several districts and wrote extensive reports on their mineral deposits and mines (Thureau 1881a, b).

Following the successful completion of his assignment, Thureau was offered the position of Tasmanian Government Inspector of Mines in 1882 (Inspector of Mines 1882, Bacon 1989). He proposed that, rather than conducting a regular and expensive geological survey with a large and permanent staff, he undertake the work "with a guide or packers" so he could "move quickly" and operate "at very much less expense" (Thureau 1883). Thureau's model was accepted and considered advantageous by the Government (Atkinson 1883).

Upon his appointment, Thureau was 50 years of age and his long association with mining had possibly impaired his health (Thureau 1881a, p. 3; Thureau sent a telegram "asking to be permitted to return to Hobart direct, instead of walking back to Bischoff, which latter I am quite unable to do, as my health has been and is very bad after the wet, fatiguing, and tedious journey"). He was about to undertake a gruelling program of exploration, journeying regularly around the island (see fig. 2). Many mines were in remote and inhospitable regions. Despite the handicaps, he undertook a systematic survey of the state's mineral resources and mines from his base in Launceston and wrote

FIG. 2 — Locations in Tasmania which Thureau inspected, assessed and included in his annual and special reports.

detailed and informative reports. During his expeditions Thureau also recorded illustrated descriptions of the island's geology, resulting in the additional title of Mining Geologist (Secretary of Mines 1887–88, p. 5).

Many of Thureau's assessments of mineral resources were undoubtedly over-optimistic (or only realised much later with improved technologies) and he has been criticised for such reports (Blainey 1969, 1993, Binks 1988). However, he certainly did not anticipate positive outcomes for all districts, and such optimism is typical of contemporary reports (Secretary of Mines 1885, 1887–88, 1888–89, Provis 1888–89). To some degree his failures may be due to the inadequacy of available analyses. However, consultancies for mining companies might, in some instances, have compromised "detached" reports for the Government. Given the climate of speculation surrounding mining, his onerous duties, the strains on his health, friction arising from his Germanic mannerisms, and periodic criticisms of his work as the Inspector of Mines, there were probably occasions when Thureau felt overwhelmed by the pressures of office.

Importantly, Thureau was active both in encouraging Tasmania mining ventures to take advantage of improved technologies and seeking ways to improve the safety standards of its mines (Inspector of Mines 1882, 1883, 1884, Secretary of Mines 1885, 1887–88, 1888–89). One "miner" wrote in 1884: "Mr. Thureau has won the popularity of the miners ... through having reduced mining accidents almost to nil" (*The Hobart Mercury* 1884).

Thureau was a Fellow of The Royal Society of Tasmania for several years (The Royal Society of Tasmania 1884). He maintained regular contact with the society and had submissions read at its meetings but, with his residence in Launceston and frequent field trips, it seems that he could only attend meetings infrequently.

In 1885, it seemed that Thureau would be dismissed to save funds in the Mines Branch. He was devastated and requested to remain at a lower cost to the Government (Brown 1885, Thureau 1885). His position was maintained, but his salary and staff were reduced. By late 1888 Thureau's considerable duties had become too much for him. Apart from his advancing age and poor health, Tasmania's mining industry was expanding considerably. Further, it was clear to Thureau that the Government no longer desired his services and in 1889 he asked to resign rather than be dismissed (AOT Letter Book 1888a, 1888b, 1889). There is evidence that Thureau was, in fact, overburdened, in that his successor's duties were to be lightened (Secretary of Mines 1888–89, p. 5).

TWILIGHT YEARS

Following his resignation, Thureau returned to private practice initially in Launceston and then Melbourne (Blainey 1993, *The South Australian Register* 1896). He was elected a member of the Geological Society of Australasia in 1896 and subsequently to its Council, probably from 1897–1901 (Geological Society of Australasia 1896–1907). Thureau died in 1901, aged 69 years (*The Age* 1901).

CONCLUSION

Australia's nineteenth-century mining industry benefitted from the expertise of German-trained mining men, attracted by Australia's mining prospects – one of these was Gustav Thureau. Given the abrupt disruption of his German training, Thureau had a remarkable career spanning over five decades. In relation to the knowledge of his day, he made an important contribution, particularly to the development of mining geology in Tasmania, where he deserves to be seen as a figure of significance. In praise of Thureau's contribution, Secretary of Mines, Francis Belstead, stated in 1885: "It is beyond dispute that the maintenance in connection with the Department of an officer possessing scientific geological knowledge, is a valuable help to the mining community and will materially aid in the development of an industry" (Secretary of Mines 1885, p. 4).

REFERENCES

AOT [Archive Office of Tasmania] Letter Book 1888a: AB 872/3 Folio 361–362 4 December 1888.

AOT Letter Book 1888b: AB 872/3 Folio 395 17 December 1888.

AOT Letter Book 1889: AB 872/3 Folio 437 2 April 1889.

Atkinson, T.R. 1883: to Thureau G 15 August 1883 AOT PP 1885/101.

Bacon, C.A. 1989: One Hundred Years of the Department of Mines. Unpublished Report 1989/09 Tasmania Department of Mines, Hobart: pp 1–11.

Binks, C.J. 1988: *Pioneers of Tasmania's West Coast.* Blubber Head Press, Sandy Bay.

Blainey, G. 1969: *The Rush That Never Ended.* Melbourne University Press, Melbourne: p 223.

Blainey, G.N. 1993: *The Peaks of Lyell.* St. David's Park Publishing, Hobart: 370 pp.

Brown, N.J 1885: to Thureau, G. 21 July 1885 AOT PP 1885/101. [***Certificate of Naturalisation Archives Office of Tasmania*** (AOT)] 1885: CSD 13/82/1674 30 April 1885.

Cusack, F. 1973a: *Bendigo – A History.* William Heinemann, Melbourne: pp. 58, 155.

Cusack, F. 1973b: *Canvas to Campus – A History of the Bendigo Institute of Technology.* The Hawthorn Press, Melbourne: pp. 54, 58.

Geological Society of Australasia 1896–1907: Minute Book for Council and Sub-Committees of Geological Society of Australasia Box 48 Royal Historical Society of Victoria.

Giblin, W.R. 1881: to Thureau, G. 28 April 1881 AOT Min 1/1 File OA/9.

Inspector of Mines 1882: Report of Inspector of Mines for 1882 AOT PP 1883/49.

Inspector of Mines 1883: Report of Inspector of Mines for 1883 AOT PP 1884/60.

Inspector of Mines 1884: Report of Inspector of Mines for 1884 AOT PP 1885/59.

Johnston, R.M. 1885: Description of two new species of Tertiary fossil plants belonging to the genera *Eucalyptus* and *Taxites*. *Papers and Proceedings of the Royal Society of Tasmania* 335–336.

Johnston, R.M. 1900–1901: Observations regarding the recent discovery by G. Thureau, F.G.S., of a fossil reptile in the Mersey Coal Measures at Railton. *Papers and Proceedings of the Royal Society of Tasmania* 9–10.

Mackay, G. 1914: *Annals of Bendigo*, Vol 2., Mackay & Co., Bendigo: p. 143.

McMullen, G.L. 1996: "An able practical and scientific man": Gustav Adolph Hugo Thureau, German-trained mining

geologist. *Historical Records of Australian Science* **11**(2): 149–177.

Oberbergamt [Mining Office] Clausthal-Zellerfeld 1848a: Akte betr. Bergschule Disziplinarsachen 1835–1867 Fach 1854 No 18.

Oberbergamt (Mining Office) Clausthal-Zellerfeld 1848b: Akte betr. Bergschule Disziplinarsachen 1835–1867 Fach 1854 No 5.

Provis, J. 1888–9: Report of 4 August 1889. Report of the Secretary of Mines for 1888–89 AOT PP 1889/81, pp. 15–18.

Public Records Office of Victoria 1865: VPRS 759/P Proceedings in Insolvent Estates Unit 97 Record 9481 November.

Ritchie, W. 1881: to Giblin, W.R. 20 April 1881 AOT Min 1/1 File OA/9.

Secretary of Mines 1885: Report of the Secretary of Mines, 1885 AOT PP 1886/71.

Secretary of Mines 1887–8: Report of the Secretary of Mines for 1887–88 AOT PP 1888/47.

Secretary of Mines 1888–9: Report of the Secretary of Mines for 1888–89 AOT PP 1889/81).

The Age 1901: 11 March 1901, p. 4.

The Argus 1865: 27 November 1865, p. 6.

The Bendigo Advertiser 1878: 23 December 1878, p. 2.

The Colonial Mining Journal, Railway and Share Gazette 1859: **1:** 160–161.

The Colonial Mining Journal, Railway and Share Gazette 1860: **2**: 101.

The Colonial Mining Journal, Railway and Share Gazette 1861a: **3**: 89, 104, 118, 153, 166.

The Colonial Mining Journal, Railway and Share Gazette 1861b: **3**: 137.

The Hobart Mercury 1884: 17 July 1884, Supplement 1.

The Launceston Examiner 1881: 20 April 1881.

The Royal Society of Tasmania 1884: Report of the Royal Society of Tasmania for the Year 1884, p. 10.

The South Australian Register 1849a: 3 March 1849.

The South Australian Register 1849b: 7 March 1849.

The South Australian Register 1896: 6 November 1896, p. 5.

Thureau, G.1879: *Synopsis of a Report on Mining in California and Nevada, U.S.A.* Government Printer, Melbourne: pp. 3–5.

Thureau, G. 1881a: West Coast: Progress Reports on Mines by Mr. G. Thureau, FGS AOT PP 1881/82.

Thureau, G. 1881b; Ben Lomond and St. Paul's River: Report on Mines by Mr. Thureau, FGS and Port Cygnet, Oyster Cove, and Sandfly: Report on Mines by Mr. Thureau, FGS AOT PP 1881/108 and 109.

Thureau, G. 1883: to Brown, N.J. 10 August 1883 AOT PP 1885/101.

Thureau, G. 1885: to Brown, N.J. 31 July 1885 AOT PP 1885/101.

Thureau, G. 1889: The "Iron Blow" at the Linda Goldfield. *Papers and Proceedings of the Royal Society of Tasmania* 1–7.

Victoria Certificate of Naturalisation 1859: Register of Patents Book F No 3 Folio 34 22 December 1859, p. 406.

Victorian Government Gazette 1865: 1 December 1865, 2799.

(Accepted 3 May 2016)

THE LIFE AND LEGACY OF THOMAS MIDGLEY JR.

by Frank T. Edelmann

(with two text-figures and four plates)

Edelmann, F.T. 2016 (31:viii): The life and legacy of Thomas Midgley Jr. *Papers and Proceedings of the Royal Society of Tasmania* 150(1): 45–49. Chemisches Institut der Otto-von-Guericke-Universität Magdeburg, Universitätsplatz 2, 39106 Magdeburg; Germany. Email: frank.edelmann@ovgu.de.

Although little known to the general public, Thomas Midgley Jr., an American chemist and inventor, made two inventions which had fatal impacts on the Earth's atmosphere, namely tetraethyl lead as an additive to fuels and Freon 12 as a refrigerant.
Key Words: Thomas Midgley Jr., lead, tetraethyl lead, leaded fuel, Freon 12, CFCs, ozone hole.

INTRODUCTION

Thomas Midgley Jr. was an American chemist and inventor whose inventions continue to influence all of us today. He was born on 18 May 1889, in Beaver Falls, Pennsylvania. His intention was to help mankind, but two of his greatest inventions threatened life on Earth. In the end he was killed by his last invention (*Wiener Zeitung* 2014, *Spiegel Online* 2014, *Wikipedia* 2016).

THE FIRST INVENTION

Thomas Midgley Jr. (pl. 1) was born into a family of inventors, notably in the field of automobile tyres. He grew up in Columbus, Ohio, and graduated in 1911 as a mechanical engineer from Cornell University. During his time at Cornell he developed a great interest in experimentation which was to characterise his life (Midgley, Jr. 1942).

In 1916, Midgley began working at General Motors under the direction of Charles Kettering (Kettering 1947). A significant practical problem which he tackled at General Motors was the so-called "knocking" of combustion engines. Midgley discovered that this noisy engine knock could be stopped by adding certain chemical compounds to the gasoline. Such compounds are called additives. At General Motors, several additives were tested but later discarded for various reasons. For example, testing of aniline as a fuel additive led to noxious odours of the car exhaust gases (Midgley Jr. 1926).

Finally, in 1921, Midgley discovered that tetraethyl lead (or TEL) acts as an outstanding anti-knock agent in gasoline and leads to a greatly improved performance of combustion engines. Thus he was the one who invented leaded gasoline (Midgley IV 2001). In December 1922, Midgley was awarded the Nichols Medal of the American Chemical Society for the "Use of Anti-Knock Compounds in Motor Fuels" (ACS 2016). A major problem with this invention, however, was the well-known high toxicity of lead. The chemical composition of tetraethyl lead is $Pb(C_2H_5)_4$ (fig. 1).

PLATE 1 — Thomas Midgley Jr. (http://science.kukuchew.com/2008/10/21/thomas-midgley-jr/)

This is a so-called organometallic compound of lead, which means that the lead atom is directly bonded to carbon atoms. In this case there are four ethyl groups connected to the lead atom. The physical properties of such organometallic compounds are completely different from those of simple metal salts. For example, lead salts are soluble in water and have high melting points. Therefore, while lead salts are highly toxic when swallowed, they cannot easily pollute the atmosphere. The situation is completely different for organometallic lead compounds such as tetraethyl lead. Tetraethyl lead is a colourless liquid which is easily vaporised. This property of tetraethyl lead was important for its possible use as a fuel additive as it had to be miscible with the gasoline. However, it had the severe disadvantage that it could easily diffuse into the

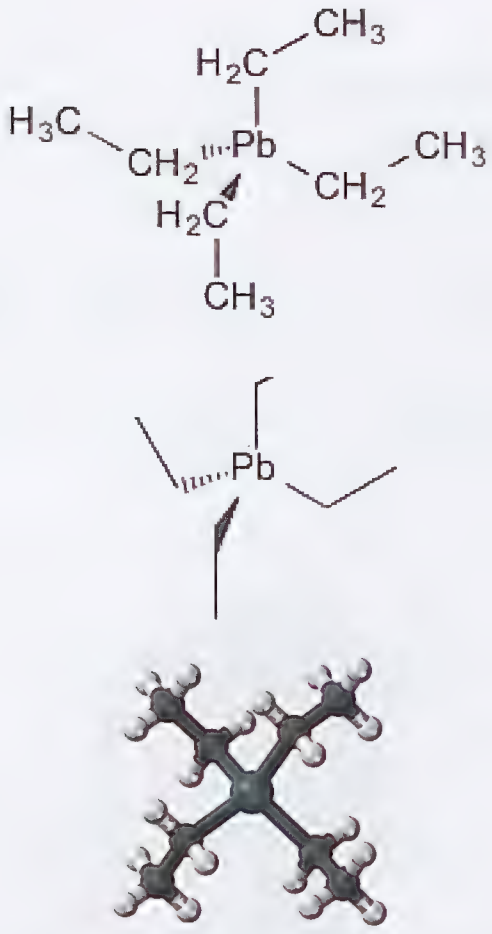

FIG. 1 — Three representations of tetraethyl lead, $Pb(C_2H_5)_4$.

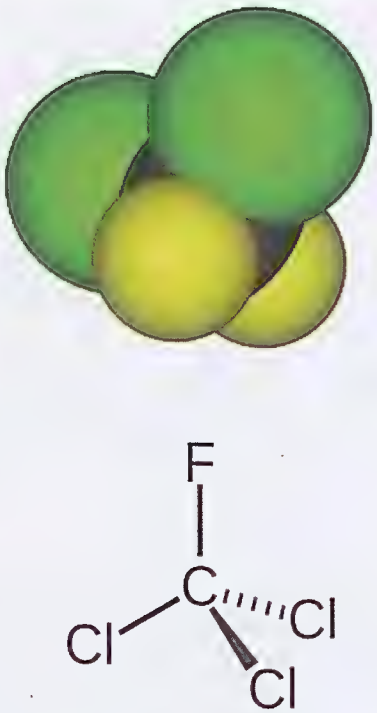

FIG. 2 — Two representations of dichlorodifluoromethane (Freon 12).

atmosphere. Even after combustion in the automotive engine, large amounts of lead particles were released into the atmosphere (Markowitz & Rosner 2003).

At that time, in the 1920s, it was well established that lead compounds are dangerous nerve poisons or neurotoxins and can lead to irreparable damage of the human brain and central nervous system. Workers producing the additive were exposed to severe health hazards. Within the first two months of production, the new plant was plagued by numerous cases of acute lead poisoning, accompanied by visual disorders, hallucinations, insanity, and five deaths in quick succession. All this was accepted by the industry (Markowitz & Rosner 2003). Too big were the promises of the new, cheap miracle cure for cars and aeroplanes. Cars changed gear faster and performed much more smoothly than before the arrival of TEL. Leaded fuel was first marketed in 1923 at a gas station in Dayton, Ohio (Midgley IV 2001).

Midgley was not only a researcher but also a successful businessman. He became the first general manager of the newly created Ethyl Gasoline Corporation, the company that produced and marketed tetraethyl lead (Midgley IV 2001).

Plate 2 shows promotional signs for leaded fuel on gasoline pumps. It is interesting to note that the full name tetraethyl lead was shortened to ethyl so that the ominous term lead would not show up on the gasoline pump.

Plate 3 illustrates newspaper advertisements of the Ethyl Gasoline Corporation intended to present leaded fuel in a positive light.

However, the toxic effects of lead were generally known and well established. As negative headlines continued, Midgley reacted with a drastic public relations move to demonstrate the harmless nature and apparent safety of TEL: On 30 October 1924 Midgley organised a press conference where, in the presence of numerous journalists, he poured tetraethyl lead over his hands. He also placed a bottle of the dangerous chemical under his nose and inhaled the vapour for 60 seconds. Then he declared: "I could do this every day without getting any health problems whatsoever." (Markowitz & Rosner 2003). In saying this, Midgley consciously lied to the journalists. Shortly after the press conference, he was diagnosed with serious lead poisoning that took more than a year to cure (Kitman 2000).

Notwithstanding the serious health risks, tetraethyl lead quickly captured the market and by summer 1925, 1.1 billion litres of leaded fuel had been sold. It took until the mid-1970s before the US began phasing out leaded gasoline. In the European Union, leaded fuel was finally banned on 1 January 2000 (Kitman 2000).

THE SECOND INVENTION

With his second great invention, Thomas Midgley Jr. indeed revolutionised everyday life around the world and perhaps even saved many human lives. He succeeded in developing cheaper and, above all, safer refrigerators. In the late 1920s, compounds like ammonia, methyl chloride or sulfur

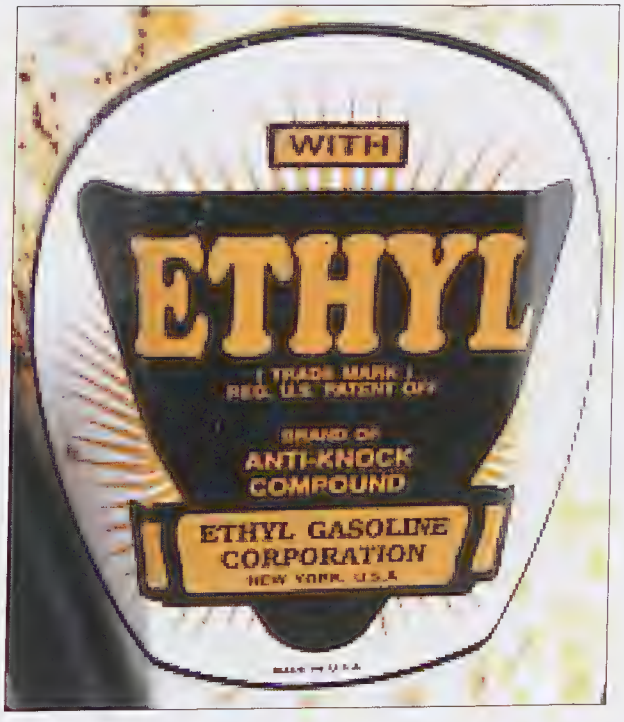

PLATE 2 — Promotional signs for leaded fuel on gasoline pumps.

PLATE 3 — Newspaper advertisements for the Ethyl Gasoline Corporation.

dioxide were employed as refrigerants in air conditioning and refrigeration systems. All these gases were either toxic, highly flammable or even explosive. The smallest leakage could result in serious illness, injury or even death.

It was Midgley who first developed a gas that replaced the numerous toxic or explosive substances previously used as refrigerants and made refrigerators safe. His new refrigerant was non-toxic and not flammable, namely dichlorodifluoromethane (Midgley IV 2001). It was the first of the chlorofluorocarbons, better known as CFCs. The CFCs form a class of chemical compounds in which some or all hydrogen atoms in hydrocarbons are replaced by chlorine and fluorine atoms. Dichlorodifluoromethane is more commonly referred to as "Freon 12". It is derived from methane, which has the composition CH_4. Figure 2 shows that in Freon 12 two chlorine and two fluorine atoms are bonded to the carbon instead of the four hydrogens.

Once again, Midgley did not back off from taking personal risks to substantiate the importance of his discovery. In 1930, he inhaled a lungful of Freon 12 and then blew out a lit candle to show the American Chemical Society that CFC was absolutely non-toxic and non-flammable (Midgley IV 2001). CFCs soon became the refrigerant of choice, and by 1950 more than 80% of American farms and more than 90% of urban homes had a CFC-cooled refrigerator (Krasner-Khait 2000). Moreover, Freon 12 and other CFCs were fantastically successful in other applications, such as air conditioning, fire extinguishers and as propellants in aerosol spray cans. The Society of Chemical Industry awarded Midgley the Perkin Medal in 1937 for his work (*C&EN News* 2008).

Midgley died three decades before the ozone-depleting (*cf.* pl. 4) and greenhouse gas effects of CFCs in the atmosphere became widely known. In 1974, the American scientists Mario Molina und Frank Rowland warned against the global threat originating from CFCs (Molina & Rowland 1974). The Montreal Protocol was signed in 1987 and in March 1988 DuPont agreed to reduce and eliminate CFC production. Worldwide production of CFCs was totally phased out by 2005.

In summary, Thomas Midgley Jr. made two inventions which had a fatal impact on the Earth's atmosphere. At the time of his discoveries, Midgley was a highly esteemed American national hero. He held two honorary degrees and in 1941 the American Chemical Society gave him its highest award, the Priestly Medal. In 1944 he was elected president of the American Chemical Society. William Lloyd Evans acknowledged his merits with the words: "In a wonderful way Thomas Midgley Jr. made life more enjoyable. The after-world will appreciate the enduring value of his research"(*Spiegel Online* 2014). Today, his legacy is viewed mainly with criticism. Midgley's inventions became an incarnation for the threats to our planet (Bryson 2012). The historian John McNeill remarked that Midgley "had more impact on the atmosphere than any other single organism in Earth's history" (McNeill 2001). A cartoon even portrayed him as the "worst scientist ever" (Doyle & Brozyna 2013).

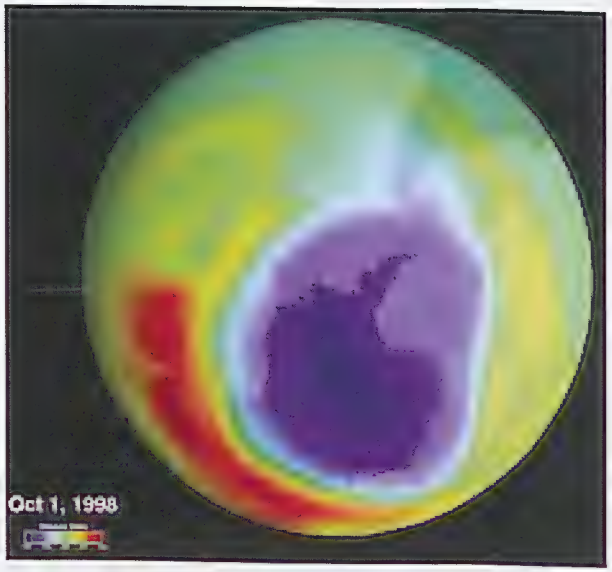

PLATE 4 — Hole in the ozone layer over Antarctica (Source: http://grin.hq.nasa.gov).

THE END

In 1940, at the age of 51, Midgley contracted polio, which left him severely disabled. This led him to devise an elaborate system of strings and pulleys to help others lift him from his bed. This system was the eventual cause of his own death when he became entangled in the ropes of this device and died of strangulation at the age of 55. This happened on 2 November 1944, in Worthington, Ohio (Bryson 2012, *Wiener Zeitung* 2014, *Spiegel Online* 2014). In all, Thomas Midgley Jr. was a tragic figure. We are still living with the consequences of his inventions and will for many years to come.

ACKNOWLEDGEMENTS

This paper was presented at the Biennial Conference of the Australian Association of von Humboldt Fellows ("Global Perspectives, Local Knowledge") in Hobart, Tasmania, 20–22 November 2015. Thanks are due to Professor John W. Gilje, James Madison University, Harrisonburg, USA, for critically reading the manuscript.

REFERENCES

ACS 2016: *Nichols Medalists*, American Chemical Society, http://newyorkacs.org/nicholsmedalists.html (accesssed 10 January 2016).

Bryson, B. 2012: *A Short History of Nearly Everything.* Doubleday, Canada.

C&EN News 2008: The Priestly Medalists, 1923–2008, *C&EN News* **86**: 60–61.

Doyle, J. & Brozyna, A. 2013: *Young Scientist's Guide to Faulty Freaks of Nature.* Gibbs M. Smith Inc.: 160 pp.

Kettering, C.F. 1947: Biographical Memoir of Thomas Midgley 1889–1944. *National Academy of Science USA Biographical Memoirs*, **24**: 359–380.

Kitman, J.L. 2000: The Secret History of Lead. *The Nation* (newspaper) of 20 March 2000, http://www.thenation.com/article/secret-history-lead/.

Krasner-Khait, B. 2000: The Impact of Refrigeration, *History Magazine* Feb./Mar. 2000, http://www.history-magazine.com/refrig.html.

Markowitz, G. & Rosner, D. 2003: *Deceit and Denial: The Deadly Politics of Industrial Pollution (California/Milbank Books on Health and the Public)*, University of California Press, USA: 428 pp.

McNeill, J.R. 2001: *Something New Under the Sun: An Environmental History of the Twentieth-Century World*, Norton, New York, USA: 421 pp.

Midgley IV, T. 2001: *From the Periodic Table to Production: The Life of Thomas Midgley, Jr., the Inventor of Ethyl Gasoline and Freon Refrigerants.* Stargazer Publishing Company, Corona CA, USA: 174 pp.

Midgley Jr., T. 1926: Prevention of Fuel Knock, *US patent No. U.S. 1,571,862* (2 February 1926).

Midgley Jr., T. 1942: A critical examination of some concepts in rubber chemistry. *Science* **96**: 143–164.

Molina, M.J. & Rowland, F.S. 1974: Stratospheric sink for chlorofluoromethanes: chlorine atom-catalysed destruction of ozone. *Nature* **249**: 810–812.

Spiegel Online newspaper 2014: Der Mann, der fast die Menschheit auslöschte (und sich am Ende selbst strangulierte). Article dated 16 May, http://www.spiegel.de/einestages/fckw-erfinder-thomas-midgley-schuld-am-ozonloch-a-968979.html.

Wiener Zeitung newspaper (Vienna) 2014: *Sorcerer's Apprentice of modern age.* Article dated 2 November, http://www.wienerzeitung.at/themem_channel/wz_reflexionen/vermessungen/686056_Zauberlehrling-der-Moderne.html

Wikipedia 2016: *Thomas Midgley Jr.*, https://en.wikipedia.org/wiki/Thomas_Midgley,_Jr. (accessed 10 January 2016).

(Accepted 7 June 2016)

APPENDIX

Biennial conference of the Australian Association of von Humboldt Fellows
in association with the New Zealand Association of von Humboldt Fellows

Hobart, 20–22 November 2015

GLOBAL PERSPECTIVES, LOCAL KNOWLEDGE

PROGRAMME AND ABSTRACTS

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Oral Lecture 1: **Prof. Shaowu Zhang**: Visually guided decision-making in foraging honeybees

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Invited Lecture 2: **Prof. Dr Frank T. Edelmann**: The life and legacy of Thomas Midgely Jr*

Invited Lecture 3: **Dr Christopher Eltschka**: Monogamy of qubit entanglement from Lorentz invariance

Abstracts Plenary Lectures

Thylacine DNA: life after death

Brandon Menzies
Department of Zoology, University of Melbourne

Marsupials have dominated the Australian landscape for the past 50 million years and still account for about 58% of its terrestrial mammals. However, the well-known legacy of mammal extinctions since European arrival, including that of the iconic Tasmanian tiger or thylacine, is a tragedy not just for posterity but also for our understanding of evolution. The thylacine was the largest extant carnivorous marsupial at the time of European settlement and remains the greatest example of convergent evolution within the mammalian lineage. That is to say, its size, body structure, and dentition were nearly indistinguishable from that of the dog or wolf. The presence of a pouch in females and the posterior positioning of the penis relative to the testes in males were the only obvious features to distinguish it as having evolved from the ancestors of the Tasmanian devil and kangaroos rather than those of wolves and man. The extinction of the thylacine is a tragedy that should inspire young scientists to understand more about our unique marsupial fauna. However, the thylacine may not have taken all of its secrets to the grave. New technologies are allowing us to piece together its genetic code so that we will soon be able to compare the sum of those pieces, the thylacine genome, with those of its doppelganger, the dog. We may soon understand the molecular processes that drove the remarkable convergence in the appearance of this unique mammal with that of man's best friend.

The challenge of funding local research in a global environment

Aidan Byrne
Chief Executive Officer, Australian Research Council

Saying how you know it: the obligatory marking of evidence

Alexandra Y. Aikhenvald
Language and Culture Research Centre, James Cook University

Every language has a way of speaking about how one knows what one is talking about. In about a quarter of the world's languages, it is mandatory to state how you know things — whether you saw the event, or heard it, or inferred it, or learnt it from another person. The grammatical markers of information source — known as "evidentials" — are an enviable feature. They help speakers be precise — and this is a cultural requirement in many smaller societies. Evidentials save us the bother of wondering "how on earth does he or she know it?" As Frans Boas, the founder of modern linguistics and anthropology, put it, "we could read our newspapers with much greater satisfaction if our language would compel them to say whether their reports are based on self-experience, inference, or hearsay." Evidentials reflect people's knowledge, experience and status. A shaman would be able to "see" what a simple mortal could not. The use of evidentials changes as speakers embrace new technologies — radio, television, internet and social media. Sadly, in the modern world small languages — where evidentials are rife — are retreating under the impact of globalisation and expansion of larger languages such as English, Spanish, Portuguese and Mandarin Chinese. The obligatory marking of evidence — and with it linguistic and cultural diversity, and local knowledge — is under threat.

Introduction to Alexander von Humboldt Foundation Programmes

Katrin Amian
Language North American, ANZ, Oceania Sponsorship and Network Division, Alexander von Humboldt Foundation Programmes

Natural chemistry – an oxymoron or reality?

Ekkehardt Hahn
Institut für Anorganische und Analytische Chemie, Westfälische Wilhelms-Universität Münster

Less than 40 years ago, chemists were considered the problem solvers: they provided new materials, new medication and new health standards. This has not changed, but the perception of chemistry in the media and the public forum is different today. Nowadays, one cannot open a newspaper without reading about some "scandal" caused by chemists or chemistry. At least in the developed world, chemists and their products are charged with pollution, environmental scandals, allergy, putting chemicals into food and so on. Who could, however, imagine life without medicals, dyes, fertilisers, soap or artificial sweeteners provided by chemists? Chemistry as a science and industry enjoys less appreciation. In spite of the fact that almost all people in developed countries, knowingly or unknowingly, benefit from the products of the chemical industry, many of them at the same time look skeptical at these products or believe that they are dangerous to the environment or even their own health. A closer inspection reveals that these convictions or better preoccupations are based on fragmentary information and wrong conclusions. Chemistry must be considered the science of the composition, the formation and the properties of all occurring substances and the science of their artificial or natural modification. In other words it is the science of the compounds which make up the stars down to substances which enable human brains to develop the spirit, which allows the material world to recognise itself. How did it happen than, that in the public opinion chemistry has become the opposite to natural and chemical has become almost synonymous with unnatural? The lecture will discuss some misconceptions developed about chemistry and demonstrate that we live in an environment exclusively made up from chemical substances.

Abstracts Invited Lectures

Functional and evolutionary insights into toxin biosynthesis of the marine dinoflagellate *Alexandrium*

Uwe John, (coauthors: Sylke Wohlrab, Gurjeet Kohli, Shauna Murray)
Helmholtz Center, Alfred Wegener Institute Bremerhaven (AWI)

Dinoflagellates are among the major groups of phytoplankton and contribute to half of the annual global primary production. However among those, some produce types of phycotoxins which can accumulate in shellfish, leading to ecosystem and human health impacts. The genus *Alexandrium*

is one of the most studied marine dinoflagellate groups due to its ecological, toxicological and economic importance. Several members of this genus produce toxic metabolites (potent neurotoxins) such as saxitoxin and its congeners that cause paralytic shellfish poisoning and polyketide synthesis (PKS) derived phycotoxins, such as spirolides and gymnodimines. We determined the phylogeny of STX-producing and other dinoflagellates. Furthermore, we determined the presence, diversity and phylogeny of sxtA, domains A1 and A4 and sxtG in *Alexandrium*, and further species of dinoflagellates. We confirmed the presence of sxtA, domain A4, in species of STX-producing dinoflagellates, and absence from nonproducing species. We investigated potential horizontal gene transfer events from cyanobacteria and studied the type of selection acting on the genes. Most genes have been replaced by dinoflagellate paralogues, others show signs for positive (diversifying) selection, paralogues presumably not involved in toxin synthesis in some strains indicating pressure for diversification of function. We found negative selection in clades of sxtG and sxtA1, clade 2, that may be directly involved in toxin synthesis, suggesting that they were functionally constrained. We studied the PKS genes in dinoflagellates and compared it with the evolution of the fatty acid synthesis (FAS) both of which have a common history. Secondly, we studied the PKS diversity within 46 species and discuss the results in respect to secondary metabolite functional evolution. Evolutionary, PKS in dinoflagellates are Type I but were apparently expressed as monofunctional proteins, a feature typical of Type II PKS. Dinoflagellate transcripts encoded a single ketoacylsynthase (KS) domain with poly A and a dinoflagellate specific splice leader (SL) sequences at the 5'UTRs. In addition, the sequenced transcripts harbored a previously unknown, apparently dinoflagellate specific conserved N-terminal domain. We discuss the implications of this novel region with regard to the putative monofunctional organisation of Type I PKS in dinoflagellates evolved through the dinoflagellate specific genomic features.

The life and legacy of Thomas Midgley Jr.*

Frank T. Edelmann
Chemisches Institut, Otto-von-Guericke-Universität Magdeburg

This talk gives a short overview on the life and legacy of the American chemist, engineer, and inventor Thomas Midgley Jr. Although little known to the general public, it is said that Midgley "had more impact on the atmosphere of our planet than any other single organism in Earth's history". In the 1920s he invented leaded gasoline, which resulted in the release of large quantities of lead into the atmosphere, causing serious long-term health problems. Later, Midgley developed the use of chlorofluoro-carbons (CFCs) as refrigerants. He died in 1944, three decades before the ozone-depleting and greenhouse gas effects of CFCs became widely known. His last invention killed him at the age of 55. Thomas Midgley Jr. was one of the most unfortunate and tragic figures of the twentieth century.

Monogamy of qubit entanglement from Lorentz invariance

Christopher Eltschka
Institut für Theoretische Physik, Universtät Regensburg

A striking result from nonrelativistic quantum mechanics is the monogamy of entanglement, which states that a particle can be maximally entangled only with one other party, not with several ones. While there is the exact quantitative relation for three qubits and also several inequalities describing monogamy properties it is not clear to what extent exact monogamy relations are a general feature of quantum mechanics. We prove that in all many-qubit systems there exist strict monogamy laws for quantum correlations. They come about through the curious relation between the nonrelativistic quantum mechanics of qubits and Minkowski space. We elucidate the origin of entanglement monogamy from this symmetry perspective and provide recipes to construct new families of such equalities.

Abstracts Oral Lectures

Visually guided decision-making in foraging honeybees

Shaowu Zhang
Australian National University

Honeybees can easily be trained to perform different types of discrimination tasks under controlled laboratory conditions. This review describes a range of experiments carried out with free-flying forager honeybees under such conditions. The research done over the past 30 or so years suggests that cognitive abilities (learning and perception) in insects are more intricate and flexible than was originally imagined. It has become apparent that honeybees are capable of a variety of visually guided tasks, involving decision making under challenging situations: this includes simultaneously making use of different sensory modalities, such as vision and olfaction, and learning to use abstract concepts such as "sameness" and "difference." Many studies have shown that decision making in foraging honeybees is highly flexible. The trained animals learn how to solve a task, and do so with a high accuracy, but when they are presented with a new variation of the task, they apply the learnt rules from the earlier setup to the new situation, and solve the new task as well. Honeybees therefore not only feature a rich behavioral repertoire to choose from, but also make decisions most apt to the current situation. The experiments in this review give an insight into the environmental cues and cognitive resources that are probably highly significant for a forager bee that must continually make decisions regarding patches of resources to be exploited.

Beyond the standard model: the variation of fundamental constants in space/time

Peter Schwerdtfeger
New Zealand Institute for Advanced Study

Fundamental constants like the speed of light, c, the Planck constant, h, or the gravitational constant, G, play defining roles in physics and chemistry. Modern theories attempting to unify all four fundamental forces of nature suggest that all fundamental constants may vary in space and time. The search for such small variations currently constitutes one of the most exciting areas of modern physics as it goes beyond

the standard model in particle physics. In fact, this area of research is motivated by new theories unifying gravity with the other three fundamental interactions, as well as by a number of cosmological models. From atomic clock experiments we already know that the variation of the fine structure constant, $\Delta\alpha/\alpha$, is less than ~10^{-17} per year, and the variation in the electron to proton mass ratio, $\Delta\mu/\mu$, ($\mu = m_e/m_p$) is similarly small with less than ~10^{-15} per year. Quasar and Big Bang nucleosynthesis data gave hints for non-zero variations, which, however, have not been firmly confirmed yet. For further progress in this area it is important to find enhanced effects in atoms or molecules for the variation of fundamental constants.

Water: a simple but elusive molecule

Richard Sadus
Swinburne University of Technology

Water is arguably one of the best-known molecules on Earth. It is certainly one of the most important, playing an essential role in supporting life. We quench our thirst with it, grow our crops with it, bathe in it, ski on it and unfold umbrellas to protect us from it. It's simple. If you stop a layperson in the street, there is a very high likelihood that they will know its chemical formula (H_2O), most will be able to identify its constituent atoms (hydrogen and oxygen) and some will also recall its triangular structure from their school days. An educated layperson might also recall the term hydrogen bonding associated with water. In view this familiarity, we should be able to predict its properties without difficulty but we can't. It's complicated. Indeed, predicting it properties has been identified as one of the great challenges in science. The theoretical treatment of water has advanced significantly since the pre-computer days that were reliant literally on "ball and stick" modelling. The main theoretical advances have come courtesy of molecular simulation techniques that make use of supercomputing to directly calculate the forces and energies of a given water model. Despite these computational advances, and indeed the apparent molecular simplicity of water, an accurate model has proved elusive. It has been estimated that there are at least 80 water models, some more commonly used than others. Typically, a model designed specifically for one property, such as diffusion, yields inadequate agreement for another property, such phase coexistence. Overcoming this situation is imperative, because accurately modelling water impacts on our ability to correctly model large systems, such as biological entities. This work surveys progress in this field and highlights the importance of an often-neglected aspect of modelling water, namely correctly accounting for the effects of polarisation.

Mt John University Observatory at fifty years*

John Hearnshaw
University of Canterbury

Mt John University Observatory at Lake Tekapo is New Zealand's only professional research observatory for optical astronomy. It was founded in 1965 as a joint institution of the universities of Pennsylvania and Canterbury, in order to give the Pennsylvania astronomers access to the southern sky. Pennsylvania's support for Mt John disappeared by 1980, but Canterbury's interest in astronomy steadily grew, and astronomy became an important part of the teaching and research in Canterbury's Department of Physics and Astronomy. In spite of funding crises, personality battles, a student demonstration and even a destructive fire, Mt John survived and thrived. Canterbury designed and built the 1-m McLellan telescope in the early 1980s and in 2004, a 1.8-m telescope was installed as a joint project with Nagoya University, in a project to detect extrasolar planets by microlensing. In the last ten years Mt John has also become a mecca for astro-tourists, who have come to appreciate the pristine dark sky of the Mackenzie and the beautiful landscape seen from the observatory. Mt John is now 50 years old and a symposium was held at Lake Tekapo in May 2015 to mark the anniversary. The symposium celebrated 50 years of outstandingly successful research and the 175 graduate student theses that have come from Mt John data; but it also pondered the uncertain future for the observatory as recent funding cut-backs have curtailed its current programmes and development.

The history of Mt John is described in a recent book, *Mt John – the first 50 years: a celebration of half a century of optical astronomy at the University of Canterbury*, by J. B. Hearnshaw and A. C. Gilmore, Canterbury University Press, Mar 2015, 216 pp., ISBN 978-1-927145-62-3.

Single crystal to single crystal phase-transition of CuQ_2-TCNQ molecular crystals- a neutron spectroscopy study

Dehong Yu (coauthors: G. J. Kearley, G. F. Liu, R. A. Mole, G. Mcintyre and X. T. Tao)
Australian Nuclear Science and Technology Organisation

Recently, a single-crystal-to-single-crystal (SCSC) phase transition with remarkable dimension changes, under mechanical stimulation, has been observed in a molecular crystal 7, 7, 8, 8-tetracyanoquinodimethane-p-bis (8-hydroxyquinolinato) copper(II) (CuQ_2-TCNQ, form-II). At the transition from form-II to form-I the crystal undergoes about 100% increase in length and 50% reduction in thickness. The discovery has attracted great interests as it shows that the CuQ_2-TCNQ may have potential applications as a molecular actuator. The phase transition mechanism of the molecular crystals has been studied with the combination of neutron spectroscopy, molecular dynamic (MD) simulation and Hirshfeld surface analysis. Inelastic neutron scattering and MD simulations have shown softening of phonon modes related to intralayer H-bonds upon phase transition from From-II to Form-I. It is shown that the strong H-bond interactions keep the in-plane atomic arrangement, while the re-optimisation of the interlayer π-π interactions provides the coupling between layers during the phase transition. This nature collaboration maintains the integrity of the crystal during phase transition.

Acknowledgement: The authors would like to acknowledge the Bragg Institute at ANSTO for the allocated beam time on the Pelican instrument. This work was supported by the National Natural Science Foundation of China (grant no. 51321091).

Unmanned aerial vehicles and ore deposits
Nicholas Jansen
CODES, ARC Centre for Excellence in Ore Deposits, University of Tasmania

My fascination and subsequent inspiration with geology began as a bush pilot flying geologists in the Canadian north. After a number of years of studying around the world as an economic geologist, I am seeking to continue my research career by combining geology with flying. Unmanned Aerial Vehicles (UAV), more commonly referred to as drones, are becoming increasingly common in our everyday lives, and for good reason, as they provide a unique aerial perspective at a significantly lower cost than traditional aircraft platforms and can be used in inaccessible and dangerous areas.

I specialise in Short Wave Infrared Spectroscopy (SWIR) which is an effective technique in identifying key minerals in many types of ore deposits. The distribution and key features in the SWIR spectrum of minerals can provide information on exploring for ore deposits, exploiting resources and subsequent environmental remediation.

My colleagues and I are developing a research project to attach SWIR spectrometers to UAVs so that we provide a unique perspective for geologists exploring, mining and remediating an ore deposit. We will discuss the challenges and opportunities to develop a UAV platform with a SWIR spectrometer and how it can be used in the mining sector.

How large pseudorandom number generators do we need in scientific computing?
Krzysztof Pawlikowski
University of Cantebury

As science becomes more and more computational, more and more complex random processes and phenomena are investigated. Empirical studies conducted by means of computers can require generation of huge sequences of (pseudo)random numbers. Demands for extremely large numbers of pseudorandom numbers occur for example during simulation studies of long-range dependent processes occurring in the Internet or if considering rare events on financial markets.

Algorithmic generators of independent and uniformly distributed numbers are used in such studies as primary sources of randomness. They generate numbers in cycles, so, as the computing technology accelerates, the cycles need to be longer, to avoid deterministic repetitions of randomness. About 20 years ago, using algorithmic generators of random numbers with cycles of the order between 231 and 248 was generally acceptable. However, these cycles have become insufficient for modern fast multiprocessor computers of the twenty-first century. New generators, with cycles exceeding 2 120 000, have been proposed. However, how long cycles are really needed if one takes into account possible fast advances of electronic and computer technologies in next 20–30 years? We will assess the cycle lengths of both linear and non-linear algorithmic generators needed in the foreseeable future, in their computationally demanding applications in statistically accurate scientific computing.

Can we look inside the brain?
Hans Bachor
Australian National University

Lasers have many uses — from communication to welding. Laser surgery is well known. Now an additional opportunity is arising: we might be able to look inside the brain and see its operation. Will we be able to understand how the brain works or help with public health. The future will show. This talk summarises work from the last few years in the area of bio-photonics, carried out at the ANU with partners in Europe and in particular Germany.

Malaria elimination: shifting priorities in malaria drug discovery research
Katherine Andrews
Griffith University

The World Health Organisation estimates there were ~198 million clinical cases and 584 000 deaths due to malaria in 2013. While this represents a decline in morbidity and mortality over the past decade, all currently used antimalarial drugs are now under threat due to parasite drug resistance. This places recent gains in a precarious situation. While new formulations/combinations of existing drugs are helping to prolong our current chemotherapeutic arsenal, no new chemical class (chemotype) of antimalarial has been introduced since 1996 and only one has entered advanced clinical trials in the past decade (spiroindolones). With ~3.2 billion people at risk of malaria and a global agenda focused on eradication, there is an urgent need to develop new drugs with novel modes of action for both the prevention and treatment of malaria. In this presentation the changing priorities in malaria drug discovery will be discussed.

The meaning of quantum in 'Quantum Electronics'
Jared Cole
RMIT University

Superconductivity, the flow of current without dissipation at sufficiently low temperatures, is one of the most surprising properties of metals. Even more surprising is that when two pieces of superconducting metal are separated by an ultra-thin region of insulator (a Josephson junction), their current and voltage characteristics depend on the quantum mechanical phase of the superconducting current on either side, the so-called DC and AC Josephson effects. The relationship between current, voltage and quantum mechanical phase is precisely defined through the laws of quantum mechanics. This links the microscopic world of quantum theory, with its wave-functions, superpositions and entanglement, to the macroscopic world of currents, voltages and high precision electronics. The connection between these two fields, combined with modern nano-fabrication techniques, is central to the burgeoning field of superconducting quantum electronics. I will discuss some of the recent advances in this field as well as looking into the future.

Superconductivity: about an unusual phenomenon in an unusual material
Eva Anton
Victoria University of Wellington

Superconductivity was discovered more than 100 years ago by Kamerlingh Onnes. His experiments showed that certain materials lose their resistance at very low temperatures. At first one could have believed that these materials become merely ideal conductors, that means for a lack of impurities and other disturbances the currents can flow without encountering any resistance. But later research raised doubts about that: the resistivity was not only very small, but actually zero, which would require a purer and colder material than can practically be achieved. In 1933 another effect was discovered by Meissner and Ochsenfeld: superconductors expel magnetic fields. It became clear that superconductivity did not just mean perfect conductivity, but is actually a new phase of matter with unique properties. Only in 1957, 46 years after the first observation of superconductivity, a theory published by Bardeen, Cooper and Schrieffer could explain the relevant phenomena known for superconductors at that time. But soon after new discoveries challenged the theoretical understanding of superconductivity: high temperature superconductivity was found in ceramics in 1986 and in iron-based superconductors in the 2000s. Recently, we found superconductivity in SmN, a ferromagnetic and semiconducting material, so far a unique combination. This talk will give an overview over superconductivity from the early experiments to our current research on a novel superconducting material.

Charged particle accelerators on a table top
Robert Robson
Griffith University

This paper discusses the prospects of laser-driven plasma-based accelerators, which offer the possibility of producing high quality, highly relativistic bunches of electrons in the laboratory, for investigations in fundamental particle physics, on a scale many orders of magnitude less than conventional accelerators.

The autocatalytic keto-enol tautomerisation of malonic acid
Catherine Sutton
University of Melbourne

Malonic acid is an important constituent of secondary organic aerosol that is present in the atmosphere. The enol tautomer of malonic acid is highly reactive but, until recently, has been believed to be present in negligible quantities, as forming it is energetically unfavourable. We demonstrate through quantum chemical calculations that the keto-enol tautomerisation of malonic acid can be catalysed by the two tautomers of malonic acid itself. This autocatalytic process proceeds with a very low barrier (Gibbs energy ca. 13 kcal/mol in the gas phase, 20 kcal/mol in continuous aqueous solution), and involves the concerted transfer of two protons between the substrate and the carboxylic acid functionality of the malonic acid catalyst. This mechanism is expected to compete with the higher-energy proton relay mechanism currently favoured to explain the tautomerisation of malonic acid in aqueous media.

The development of a novel immunoglycotherapy for the treatment of Non-Hodgkin's Lymphoma
Thomas Haselhorst
Griffith University

Siglecs (sialic acid binding immunoglobulin-like lectins) play a wide variety of important roles in the immune system and consequently targeting these lectins provides exciting opportunities for therapeutic intervention in immunological disorders or cancer. Siglec-2 (CD22) has become an attractive target for the discovery of autoimmune disease therapies and B cell derived non-Hodgkin's lymphoma (NHL).

We have explored the design of a novel class of C-4- and C-9- substituted a-methyl glycosides of N-acetylneuraminic acid based on a homology model of Siglec-2, extensive NMR binding experiments and biological evaluation.

The synthesis and biological evaluation of these derivatives provided an inhibitor that has nanomolar affinity to this Siglec and may provide a pathway for immunoglycotherapy strategies.

Ripples in the fabric of space-time*
Joerg Frauendiener
University of Otago

Gravitational waves are one of the most elusive phenomena in nature. Predicted by Einstein in 1917 they have yet to be detected directly on earth even though there is plenty of theoretical and indirect observational evidence for their existence. This talk will describe their basic properties and how, we believe, we can detect them.

Formation of the largest platinum deposit on Earth - what we learn from µm-scale observations*
Lennart Fischer (coauthors: Bernard Charlier, Olivier Namur, Francois Holtz)
Leibniz Universität Hannover

The Bushveld Complex in South Africa is the largest layered intrusion on Earth and plays a considerable role in our understanding of magmatic and ore-forming processes. Formed from 1 million km^3 magma, it covers now a 65 000 km^2 area with a thickness of 7–9 km. In this giant volume, world major resources of platinum (and other Pt group elements), iron, titanium, vanadium, tin, and chromium are hosted. The Bushveld Complex is the world's largest resources of platinum group elements. Discovered in 1897 it is still one of the most important mining areas.

The Bushveld Complex was formed by several injections of magma into the Earth's crust. With time and cooling, minerals crystallised and settled in the magma chamber, forming a rock with horizontal layering. The enrichment in valuable elements, such as platinum, varies in each layer. This makes it important to understand the processes involved in forming the layers and the resulting enrichment or depletion of economically interesting elements.

To understand these processes we combine the study of natural Bushveld Complex rocks with experiments. Since melts initially present at the onset of the Bushveld formation are now completely crystallised, information on magmatic stages can only be gained from the investigation of micrometer-scale inclusions in natural crystals, representing former pockets of melts prior to the solidification of the

intrusion. These results are complemented with experiments at temperatures between 1000°C and 1200°C and a pressure of 200 MPa (~6 km depth), corresponding to conditions similar to the formation of the Bushveld Complex. These experiments simulate the evolution of the magma and allow us to study different stages of the magmatic history of the Bushveld Complex.

Alexander von Humboldt, electricity and muscle contraction

Alexander Davies
Massey University

In the final years of the eighteenth century, there was widespread interest in a new tool discovered by Luigi Galvani in Bologna. Muscles and nerves were stimulated when in contact with a combination of different metals. Alexander von Humboldt conducted over 4000 experiments on the effects of various metals on preparations from frogs and other animals, plants, and on his own body. However, like nearly all of the many who made similar studies, he thought that the electricity came from living tissues, as was the vital spirit supposed since classical Greek and Roman times, not from the metal combination. For the rest of his life, Humboldt regretted that Alessandro Volta had beaten him to the correct conclusion. What might Humboldt's career have become had the voltaic pile been a humboltic pile?

The Year of Soils 2015: celebrating soils in Australia and globally

Thomas Baumgartl
The University of Queensland

The 68th UN General Assembly declared 2015 the International Year of Soils. This is considered a milestone in the soil science community to raise awareness and inform civil society and decision makers on the importance of sustainable soil management as the basis for food systems, fuel and fibre production, essential ecosystem functions and better adaptation to climate change for present and future generations.

Soils fulfil a multitude of roles and purposes. Soils provide food security, climate change adaptation and mitigation and essential ecosystem services. Soils alleviate poverty and are the basis for sustainable development in general. For soils to fulfil these objectives, they are required to be managed sustainably and their protection has to be anchored in national and international legislations.

This contribution presents some background on the origin of soils and their main properties and functions. Soils are under threat by a multitude of users and such issues have to be understood and managed, e.g., the competing land use between prime agricultural land and resource extraction, which is discussed currently in Australia. Globally, soils have to be understood as a non-renewable resource for food supply for a growing population. However, challenges lie ahead and have to be dealt with to satisfy the growing demands on soils.

Quantum phase slip elements: exploiting duality in quantum circuits

Nicholas Vogt
RMIT University

In the last thirty years it has become possible to realise some of the most fundamental experiments of quantum mechanics in electrical systems. In pursuing the goal of creating the building blocks of quantum computers, ultra-cold superconducting circuits have been developed that provide an artificially constructed quantum system, sometimes also referred to as artificial atom, on a chip. These systems are usually based on Josephson junctions, insulating contacts between two superconductors. In recent years it has become possible to fabricate new circuit elements for superconducting circuits, the quantum phase slip elements (QPS-elements). These elements are dual to Josephson junctions, they have the same function when the roles of current and voltage are exchanged. We now have the opportunity to find ways to exploit this duality to improve the properties of superconducting circuits as artificial quantum mechanical systems.

Hans Hermann Behr (1818–1904), botanist, entomologist, anthropologist, humourist and dangerous?*

Allan Bretag
University of South Australia

Unlike Hans Hermann Behr, who was born in Cöthen, Saxony, I was raised in the Zoological Park (then my parents' farm) at Monarto, South Australia, where I first came across Behr in my youth. Strictly, my introduction was to *Lasiopetalum behrii*, a beautiful, pink-flowering shrub growing on the property. Behr arrived in Adelaide in late 1844 as a newly graduated doctor interested more in botany, entomology and anthropology. After just one year, he returned to Germany with prolific samples and notes, having made collections and short explorations to the immediate north and east of Adelaide. These were quickly assembled for publication but, in his own subsequent words, "I was young, a socialist, and emancipation-mad in different directions", and, "In the glorious year of 1848 I had been guilty of all sorts of misdemeanours, [and] looked upon myself as a very dangerous kind of person". Forced to leave Germany, he returned to Adelaide towards the end of 1848, again collecting extensively (including with Ferdinand von Mueller, who formally described Behr's Pink Velvet Bush in 1855). Within a year he had left for The Philippines and after another year or so had arrived in San Francisco where he firmly established his international reputation.

Conserved genes for fungal sexual development and fungal-plant symbiosis

Barry Scott
Massey University

Epichloë festucae is a filamentous fungus that forms a mutually beneficial symbiotic association with *Lolium perenne*, perennial ryegrass. This biotrophic fungus systemically colonises the intercellular spaces of both vegetative and reproductive aerial tissues to form a highly structured and interconnected symbiotic hyphal network. The fungus benefits from this association by access to nutrients from the plant

and vertical transmission through the seed. The grass host benefits from the bioprotective metabolites synthesised by the fungus.

To identify fungal genes crucial for maintaining this symbiosis we generated a series of mutants that no longer formed a mutualistic interaction; the growth of the mutant hyphae was no longer restricted leading to colonisation of the vascular tissue, premature senescence and death of the host. Analysis of these genes revealed they are components of a conserved regulatory network controlling the onset of sexual fruiting body development in other filamentous fungi. The common link between these two developmental processes appears to be a requirement for cell-cell chemotropic homing and cell-cell fusion.

These results lead to the hypothesis that there is a conserved regulatory network controlling fungal sexual development and fungal-plant symbiosis.

Autism: a story from molecules to mind

Charles Claudianos
Monash University

The development of the nervous system occurs in two ways; that which is determined by our genetic program helping to direct cells to replicate and differentiate, producing neurons that can project, connect with other neurons, innervate muscle and tissues typical of a developing fetus and; that which requires the same genetic program to respond to environmental stimuli, learn, acquire and recall memory and is subject to constant cellular/neuronal remodeling throughout life. Within this framework I will present recent advances in understanding the biological basis of neurodevelopmental disorders such as autism. We use an integrated 'molecules to mind' approach to examine human DNA variations found in affected individuals and their families. Cutting edge genomic and cellular technologies are helping us unravel the impact of defective genes on key biological processes including how nerve cells connect in the brain. Similarly, the biological relevance of genes in behaviours that are indicative of autism such as learning and memory and sleep defects are examined using small animal models. These approaches allow us to 'join the dots' and better understand what causes mental disorders such as autism.

Cosmology-Topology/Geometry: mathematical evidence for the Holographic Principle*

David Glynn
Flinders University

In August 2015 NORDITA (Nordic Institute for Theoretical Physics) hosted a conference where Hawking strongly supported the conjectured relationship between string theory and quantum fields that was initiated with the holographic principle some 20 years ago by 't Hooft, Maldacena, Susskind and Witten; see https://en.wikipedia.org/wiki/AdS/CFT_correspondence. Now mathematics can come to the party showing how the fundamentals of flat (even higher-dimensional) space can be derived very simply from topological properties on a surface. Specifically we show that Desargues, Pappus and other configurations do not have to be assumed a priori or self-evident (a fundamental weakness of Hilbert's work 1899) to develop the foundations of geometry. Are black holes places where non-commutative (quantum) behaviour reigns while Euclidean (flat) space is where commutativeness holds sway? So we cannot hope to look inside a black hole unless we know how "deformable" topology is related to "flat" geometry.

Gustav Thureau, first Tasmanian Inspector of Mines and Government Mining Geologist*

Gabrielle McMullen
Australian Catholic University

From humble origins as a rebellious student in Clausthal, Germany, Gustav Thureau became the first Tasmanian Inspector of Mines and Government Mining Geologist. He qualified himself for these offices by working in Germany, then Australia and briefly America as a miner, mine manager, lecturer, mining inspector, mining reporter and mining consultant. His remarkable career, associated with mining for over 50 years, is interspersed with a number of controversies.

Ernst Chladni's theory of chimes and three-dimensional solitary waves in atomic superfluids

Joachim Brand
Massey University

Eighteenth century German scholar Ernst Florens Friedrich Chladni discovered how sand strewn on a vibrating plate produces patterns that are characteristic of the sound emitted by the vibration. The mathematics of vibrating plate patterns has been well developed since the time of Chladni but only very recently has a connection been made to the structure of solitary waves in confined atomic superfluids. In this talk I will explain the connection between Chladni figures of sound and observations made in recent experiments with ultra-cold and superfluid Fermi gases.

JRNL G-39

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Multiple author paper:

Ainley, D. G., Veit, R. L., Allen, S. G., Spear, L. B. & Pyle, P. 1995: Variations in marine bird communities of the California current, 1986–1994. *California Cooperative Oceanic Fisheries Investigations Reports* **36**: 72–77.

Book:

Davison, A. C. & Hinkley, D. V. 1997: *Bootstrap Methods and their Application*. Cambridge University Press, Cambridge: 592 pp.

Edited work:

Marchant, S. & Higgins, P. J. (eds) 1993: *Handbook of Australian, New Zealand and Antarctic Birds. Volume 2: Raptors to Lapwings*. Oxford University Press, Melbourne, Australia: 1048 pp.

Chapter in an edited work:

Artyukhin, Y. B. & Burkanov, V. N. 2000: Incidental mortality of seabirds in the drift net salmon fishery by Japanese vessels in the Russian Exclusive Economic Zone, 1993–1997. *In* Kondratyev, A. Y., Litvineko, N. M. & Kaiser, G. W. (eds): *Seabirds of the Russian Far East*. Ottawa, Canadian Wildlife Service Special Publication: 105–116.

Thesis:

Charleton, K. J. 2002: Variation in Sooty Shearwater burrow entrance density, burrow use and chick emergence: Science and Traditional Environmental Knowledge approaches. Unpublished MSc thesis, University of Otago, Dunedin.

Electronic version of journal:

Chiswell, S. M. & Rickard, G. J. 2006: Comparison of model and observational ocean circulation climatologies for the New Zealand region. *Journal of Geophysical Research* **111**: C10011, doi:10.1029/2006JC003489.

Website:

IUCN 2001: *IUCN Red List of Threatened Species 2001 Categories & Criteria (version 3.1)*, www.iucnredlist.org (accessed 22 January 2007).

Report:

MacKenzie, D.I. & Fletcher, D. 2005: Characterisation of seabird captures in NZ fisheries. Report to Ministry of Fisheries for Project ENV2004-04. April 2006. Unpublished Report to the Ministry of Fisheries, Wellington: 99 pp.

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Correlation coefficients between spatial properties of Wedge-tailed Shearwater burrows at Radar Reef, Rottnest Island

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